# MONTHLY WEATHER REVIEW

VOLUME 79 NUMBER 3

MARCH 1951

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U. S. DEPARTMENT OF COMMERCE · WEATHER BUREAU

## CORRECTION

MONTHLY WEATHER REVIEW, February 1951, Vol. 79, No. 2, cover: In table of contents, article by Klein should appear opposite page 35, article by Miller and Vederman opposite page 39.

DEPARTMENT OF COMMERCE
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# MONTHLY WEATHER REVIEW

Editor, JAMES E. CASKEY, JR.

Volume 79
Number 3

MARCH 1951

Closed May 15, 1951
Issued June 15, 1951

# PERSISTENCE OF EXTREMELY WET AND EXTREMELY DRY MONTHS IN THE UNITED STATES [1]

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[Manuscript received February 9, 1951]

## ABSTRACT

**Statistical tests based on comparisons of observed occurrences of extremely wet and extremely dry months at 46 stations and 4 areas in the United States with occurrences predicted by the binomial theorem indicate that there is a tendency for persistency of extremely dry months.**

## INTRODUCTION

Many of the statistical problems in climatology involve the question of dependence or independence between precipitation amounts for consecutive periods. This paper presents a study of consecutive monthly precipitation amounts, which will follow a review of results obtained by other investigators for similar studies.

## REVIEW OF EARLIER RESULTS

Gold [1] compared the frequencies of isolated sequences of "rain" and "fine" days at Kew, England, over a 10-year period with the probable number of sequences of 1, 2, 3, etc., days that pure chance would give. His conclusions were that frequencies of sequences of 6, 7, 8, 9, and 10 days occurred more often than pure chance would indicate. Hawke [2] applied Gold's probability numbers to "wet" and "dry" months from 1841 to 1930 at Greenwich. He showed that sequences of 1, 3, 5, 6, and 15 months of the same precipitation character occurred more often than expected but not significantly so. Bilham [3] also used Gold's chance probabilities for wet (above normal) and dry (below normal) months over England and Wales. His conclusions were: 1. Isolated dry and wet months were less frequent than chance would indicate. 2. Runs of five or more months (wet or dry) occurred more frequently than indicated by chance. 3. Runs of three or more dry months occurred distinctly more frequently than runs of three or more wet months.

Cochran [4] extended Gold's probabilities so that they would include cases where the chance occurrences of two events are not equal. He set up table 1 in which wet and dry months are defined as being above and below normal, respectively. Expected frequencies, computed from marginal totals, are shown in parentheses.

TABLE 1.—*Contingency table showing freauency of wet and dry current months against wet and dry preceding months. Expected frequencies are shown in parentheses. England and Wales, 1727–1934 (after Cochran)*

| | | Preceding month | | Total |
|---|---|---|---|---|
| | | Wet | Dry | |
| Current month | Wet | 542 (513) | 582 (611) | 1, 124 |
| | Dry | 582 (611) | 759 (730) | 1, 341 |
| | Total | 1, 124 | 1, 341 | 2, 465 |

From the table, the proportion of wet months if the previous month was wet is $542 \div 1124 = 0.4822$ with standard error $= \pm 0.01485$; the proportion of wet months if the previous month was dry is $582 \div 1341 = 0.4340$ with standard error $= \pm 0.01360$. Thus a tendency toward persistence is indicated. Cochran then found a standard

[1] This paper was prepared as part of a cooperative project of the U. S. Department of Commerce, Weather Bureau and the U. S. Department of the Interior, Bureau of Reclamation.

error of $\pm\sqrt{(0.01485)^2+(0.01360)^2}=\pm 0.02013$ for the difference between the fractions and points out that the probability that this or a greater difference should arise by chance is about 1 in 60. To make this result comparable with the method to be used in this paper, we computed from his data a $\chi^2$-value of 5.55, which is significant at the 2 percent level for one degree of freedom[2]. Beer, Drummond, and Fürth [5], using the same British data, divided monthly, homogenous, long rainfall records at seven localities into two groups depending upon whether the month was above (wet) or below normal (dry) and obtained table 2.

TABLE 2.—*Contingency table showing frequency of wet and dry current months against wet and dry preceding months. Expected frequencies are shown in parentheses. British Isles 1815–1944 (after Beer, Drummond, and Fürth)*

| | | Preceding month | | Total |
|---|---|---|---|---|
| | | Wet | Dry | |
| Current month | Wet | 200 (207) | 266 (259) | 466 |
| | Dry | 269 (262) | 322 (329) | 591 |
| | Total | 469 | 588 | 1,057 |

A $\chi^2$-value of 0.588 with one degree of freedom indicates no significance at the 10 percent level.

Tannehill [6] noted that Washington, D. C., records for 1930 showed four consecutive months with precipitation amounts less than one inch: August, 0.62; September, 0.76; October, 0.28; and November, 0.79 in. Using 77 years of record he found only 4 Augusts, 6 Septembers, 12 Octobers, and 8 Novembers with less than one inch of precipitation. Under the assumption of independence, month for month, of the occurrence or nonoccurrence of monthly amounts less than 1 inch, this gave a chance value of about one in 15,000 of having each of these 4 months with less than 1 inch in the same year. He proposed that some persistent control modified the climate temporarily during the 1930 drought period.

Solot [7], investigating 40 years of Hawaiian Islands records, has presented the data in table 3 to show the lag relationship of rainfall of a given class for a given month with that of subsequent months. In this table, monthly rainfall amounts were divided into the three classes of equal observed frequency—heavy, moderate, and light.

The middle class (not shown here) does not differ significantly from chance distribution, while light rainfall is significantly related to the occurrence of light rainfall up to approximately 3 months later and heavy rainfall is significantly related to subsequent heavy rainfall up to 2 months later.

[2] Many textbooks in statistics discuss the $\chi^2$-test and its significance. For example, see P. G. Hoel, *Introduction to Mathematical Statistics*, John Wiley and Sons, New York, 1947, pp. 186–195. In judging the results of this and later applications of the $\chi^2$-test, it should be remembered that the test is insensitive to type II error, i. e., the test may fail to show dependence when some degree of dependence is present. Many other statistical tests, of course, show a similar insensitivity; although with some types of data, it is possible to use tests that are somewhat more sensitive.

TABLE 3.—*Frequency of occurrence of rainfall classes in subsequent months in Hawaiian Islands, 1905–45 (after Solot)*

[Intervening months are not considered]

| Months later | Light followed by— | | | Heavy followed by— | | |
|---|---|---|---|---|---|---|
| | Light | Moderate | Heavy | Light | Moderate | Heavy |
| | *Percent* | *Percent* | *Percent* | *Percent* | *Percent* | *Percent* |
| 1 | 45 | 34 | 21 | 20 | 31 | 49 |
| 2 | 44 | 32 | 24 | 25 | 33 | 42 |
| 3 | 41 | 34 | 25 | 30 | 31 | 39 |
| 4 | 36 | 32 | 32 | 35 | 31 | 35 |
| 5 | 33 | 35 | 32 | 31 | 31 | 38 |

Lastly, Showalter [8] classified monthly and annual precipitation at Los Angeles into three categories (wet, normal, and dry) with equal chance of occurrence and compared the observed number of successive months or years of each class with the number expected to occur by chance. His results show that successive years and successive months of the same rain character have not occurred as frequently as would be expected by chance.

Summarizing: In England there seems to be a tendency toward persistence for wet and dry months, the tendency being slightly stronger for dry months. In Hawaii there is a definite tendency for both heavy and light monthly amounts to persist up to 2 or 3 months. The investigation of the Los Angeles area indicates no persistence for monthly rainfall amounts, while for the United States in general there have not been enough tests to permit definite conclusions.

## STUDIES IN COLORADO RIVER BASIN

In a study sponsored by the United States Weather Bureau and the Bureau of Reclamation [9], from which this paper is an outgrowth, various tests of independence were used. The records of eight stations in the Colorado River Basin were checked and the frequency of occurrence of wet (above normal) and dry (below normal) October-December and January–April periods were tabulated as in table 4.

TABLE 4.—*Contingency table showing frequency of occurrence of wet and dry October–December and following January–April periods in Colorado River Basin, 1914–49. Expected frequencies are shown in parentheses*

| | | October–December | | Total |
|---|---|---|---|---|
| | | Wet | Dry | |
| January–April | Wet | 66 (60) | 68 (74) | 134 |
| | Dry | 58 (64) | 85 (79) | 143 |
| | Total | 124 | 153 | 277 |

A $\chi^2$-test on departures of actual from expected frequencies (in parentheses) gave a value of 2.2 which is not significant at the 5 percent level. A similar test on October–December, January–February, and March–April precipitation frequencies yielded a $\chi^2$-value which indicated no dependence at the 1 percent level. Correlation tests

TABLE 5.—*Correlations for average precipitation for certain periods vs. following indicated periods, Eastern Utah, 1892–1947*

| Periods | Correlation coefficient |
|---|---|
| October–December vs. January–April | 0.27 |
| October–December vs. January–February | .03 |
| October–December vs. March–April | .31 |
| January–February vs. March–April | .10 |
| October vs. November | .07 |
| November vs. December | .18 |
| December vs. January | .03 |
| January vs. February | .16 |
| February vs. March | .03 |
| March vs. April | −.16 |

were then made for 56 years of average precipitation over eastern Utah (table 5).

For 56 items at the 5 and 1 percent levels the lowest significant coefficients are 0.259 and 0.377, respectively. The z-test applied to these coefficients individually would indicate that they are not significant. The fact that 9 of the 10 are positive, though, is suggestive of some tendency toward persistence.

## EXTREMELY WET AND EXTREMELY DRY MONTHS

For a more accurate estimate of dependence of extreme values it was decided to concentrate on a study of highest and lowest precipitation amounts. Using the 50 years (1898–1947) of rainfall records at various stations in the United States, the five highest and five lowest monthly totals of precipitation for each month at each station were designated as A's and C's, respectively; all others were designated as B's. These data were prepared for a total of 46 stations and 4 areas (table 6). Of course, the data are not to be regarded as representing 50 independent stations since precipitation amounts at some of the stations are undoubtedly correlated. An example of the data for one station is shown in table 7. Stations in areas such as California were eliminated because the absence of rainfall in most summers makes it impossible to determine the five extremely low months. If a choice was necessary in designating the fifth highest or lowest value, it was standard procedure to choose the one of earliest date. With the extremely wet and extremely

TABLE 6.—*Stations and areas for which extremely high and extremely low monthly precipitation amounts were determined*

1. Albany, N. Y.
2. Alpena, Mich.
3. Atlanta, Ga.
4. Baker, Oreg.
5. Bismarck, N. Dak.
6. Boston, Mass.
7. Cheyenne, Wyo.
8. Chicago, Ill.
9. Cincinnati, Ohio.
10. Columbia, Mo.
11. Des Moines, Iowa.
12. Detroit, Mich.
13. Dodge City, Kans.
14. Grand Rapids, Mich.
15. Green Bay, Wis.
16. Helena, Mont.
17. Huron, S. Dak.
18. Kansas City, Mo.
19. Keokuk, Iowa.
20. Lander, Wyo.
21. Little Rock, Ark.
22. Madison, Wis.
23. Milwaukee, Wis.
24. Minneapolis, Minn.
25. New Orleans, La.
26. New York, N. Y.
27. North Head, Wash.
28. North Platte, Nebr.
29. Oklahoma City, Okla.
30. Omaha, Nebr.
31. Philadelphia, Pa.
32. Portland, Oreg.
33. Pueblo, Colo.
34. Rapid City, S. Dak.
35. St. Louis, Mo.
36. Salt Lake City, Utah.
37. Sault Ste. Marie, Mich.
38. Seattle, Wash.
39. Sioux City, Iowa.
40. Spokane, Wash.
41. Tacoma, Wash.
42. Topeka, Kans.
43. Tulsa, Okla.
44. Valentine, Nebr.
45. Washington, D. C.
46. Wichita, Kans.
47. Eastern Oklahoma.
48. Central Oklahoma.
49. Western Oklahoma.
50. Eastern Utah.

TABLE 7.—*Calendar of extremely wet and extremely dry months at Pueblo, Colo. For each month, A's designate 5 highest monthly precipitation totals, C's the 5 lowest, and B's all others*

| Year | Jan. | Feb. | Mar. | Apr. | May | June | July | Aug. | Sept. | Oct. | Nov. | Dec. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1898 | B | B | B | B | A | B | C | B | B | B | B | A |
| 99 | B | B | B | C | C | B | A | B | B | B | B | B |
| 1900 | B | B | B | A | B | B | B | C | C | B | B | B |
| 01 | B | B | B | B | A | B | B | B | B | B | C | B |
| 02 | B | B | B | C | B | B | B | B | B | B | B | B |
| 03 | B | A | B | B | C | A | B | B | B | B | B | B |
| 04 | B | B | B | B | B | A | B | B | B | B | C | B |
| 05 | B | B | A | A | B | B | B | B | B | B | B | B |
| 06 | B | C | B | B | B | B | B | B | B | B | B | C |
| 07 | B | B | C | B | B | B | B | B | B | B | B | B |
| 08 | B | B | B | C | B | C | B | B | B | B | B | C |
| 09 | B | B | B | B | B | B | B | B | A | B | A | B |
| 1910 | B | B | C | B | B | B | B | B | B | C | B | B |
| 11 | B | B | B | B | B | B | B | C | B | B | B | A |
| 12 | B | B | B | B | B | B | B | B | B | B | C | C |
| 13 | B | A | B | B | B | B | B | B | B | B | B | A |
| 14 | B | B | B | A | A | B | A | B | B | A | C | B |
| 15 | B | B | B | A | B | B | B | B | B | B | B | B |
| 16 | B | C | B | B | B | B | B | B | C | B | B | B |
| 17 | B | B | B | B | B | B | B | B | A | B | C | B |
| 18 | B | B | B | B | C | B | B | B | B | B | B | B |
| 19 | C | B | A | B | C | B | B | B | A | B | B | B |
| 1920 | B | B | C | B | B | B | B | B | B | B | B | B |
| 21 | B | B | B | B | B | A | A | B | B | B | B | A |
| 22 | B | B | B | B | B | B | C | B | C | B | A | C |
| 23 | C | B | B | B | B | B | A | A | B | A | B | B |
| 24 | B | B | B | B | B | B | B | C | C | B | B | B |
| 25 | A | B | B | C | B | B | A | B | B | B | A | B |
| 26 | A | C | B | B | B | B | B | B | B | B | B | B |
| 27 | B | B | B | C | B | B | B | B | B | C | B | B |
| 28 | C | B | A | B | A | B | B | C | C | B | A | B |
| 29 | B | B | B | B | B | C | B | A | B | B | B | B |
| 1930 | B | C | B | B | B | B | B | B | B | B | B | B |
| 31 | B | A | B | B | B | B | B | B | B | B | B | C |
| 32 | B | C | B | B | C | B | B | B | B | B | B | B |
| 33 | C | B | B | B | B | B | B | B | B | C | B | B |
| 34 | C | A | B | B | B | C | B | C | B | C | B | B |
| 35 | B | B | C | B | B | B | C | B | A | B | B | B |
| 36 | B | B | C | B | A | B | B | B | B | B | B | B |
| 37 | B | B | B | B | B | B | C | B | B | B | B | A |
| 38 | B | B | B | B | B | B | B | B | B | B | B | B |
| 39 | A | A | B | B | B | C | C | B | B | C | B | B |
| 1940 | A | B | B | B | B | B | B | B | A | B | B | B |
| 41 | B | B | A | B | B | B | B | A | B | A | B | B |
| 42 | B | B | B | A | B | A | B | B | B | A | B | B |
| 43 | B | B | B | B | B | B | B | B | B | B | B | B |
| 44 | B | B | A | B | B | B | B | B | B | B | B | B |
| 45 | A | B | B | B | B | B | B | A | B | B | B | B |
| 46 | B | B | B | B | B | C | B | A | B | B | A | B |
| 47 | B | B | B | B | B | A | B | B | B | A | B | B |

dry months (A's and C's) thus determined, chance frequencies based on the binomial distribution were computed and various tests were made as to whether the A's and C's occur differently than chance would indicate for a like number of A's and C's under similar constraints, i. e., 5 A's and 5 C's in each of 12 vertical columns of 50 entries each.

## FREQUENCY OF YEARS WITH FOUR OR MORE A's OR C's

The occurrence of a comparatively large number of A's or C's in some years with very few in others would be indicative of persistence, so one test consisted of counting the number of years with 4 or more A's or 4 or more C's at a station. Table 8 compares the observed and chance frequencies of the number of stations with 0, 1, 2, and 3 or more years with 4 or more A's and C's.

A $\chi^2$-value of 1.603 on the A's is not significant at the 10 percent level for 3 degrees of freedom. On the C's, $\chi^2=3.574$ is also not significant at the 10 percent level. The fact that neither value is significant indicates that there

TABLE 8.—*Comparison of observed and chance number of stations having various numbers of years with 4 or more extremely wet or extremely dry months*

| Years | Number of stations having indicated number of years with— | | Number expected by chance |
|---|---|---|---|
| | 4 or more A's | 4 or more C's | |
| 0 | 16 | 8 | 13.6 |
| 1 | 19 | 19 | 18.0 |
| 2 | 8 | 15 | 11.6 |
| 3 or more | 7 | 8 | 6.8 |
| Total | 50 | 50 | 50.0 |

is no pronounced tendency for extremely wet or extremely dry months to persist during a year, that is, for extremely wet months or for extremely dry months to occur together in the same year.

## OCCURRENCE OF EXCEPTIONALLY WET MONTHS AND EXCEPTIONALLY DRY MONTHS IN THE SAME YEAR

Another test of randomness is based on the distribution of various numbers of C's in the years in which certain numbers of A's have occurred, or, as we have tested, the frequencies of years with various numbers of C's in the same year with 2, 3, or 4 A's. Table 9 compares the observed and theoretical frequencies of occurrence of various numbers of C's and A's in years with exactly two A's or C's respectively, in the 50 years at the 46 stations and 4 areas.

TABLE 9.—*Comparison of observed and theoretical frequencies of C's and A's in years that have exactly 2 A's or 2 C's, respectively*

| Number of C's in a year with 2 A's | Observed frequencies | Chance frequencies | Number of A's in a year with 2 C's | Observed frequencies | Chance frequencies |
|---|---|---|---|---|---|
| 0 | 199 | 209 | 0 | 194 | 190 |
| 1 | 219 | 232 | 1 | 189 | 211 |
| 2 | 126 | 116 | 2 | 125 | 105 |
| 3 | 47 | 34 | 3 | 30 | 31 |
| 4 or more | 8 | 8 | 4 or more | 6 | 7 |
| | 599 | 599 | | 544 | 544 |
| With 4 degrees of freedom $\chi^2=2.566$, which is not significant at the 10 percent level. | | | With 4 degrees of freedom $\chi^2=6.338$, which is not significant at the 10 percent level. | | |

Secondly, we compare the observed frequencies of C's or A's when 3 A's or 3 C's, respectively, have occurred with the theoretical frequencies in Table 10.

TABLE 10.—*Comparison of observed and theoretical frequencies of C's and A's in years that have exactly 3 A's or 3 C's, respectively*

| Number of C's in a year with 3 A's | Observed frequencies | Chance frequencies | Number of A's in a year with 3 C's | Observed frequencies | Chance frequencies |
|---|---|---|---|---|---|
| 0 | 92 | 85 | 0 | 88 | 86 |
| 1 | 84 | 85 | 1 | 72 | 86 |
| 2 | 30 | 38 | 2 | 49 | 38 |
| 3 or more | 14 | 12 | 3 or more | 13 | 12 |
| | 220 | 220 | | 222 | 222 |
| $\chi^2=2.290$, which with 3 degrees of freedom is not significant at the 10 percent level. | | | $\chi^2=3.734$, which with 3 degrees of freedom is not significant at the 10 percent level. | | |

Lastly, in table 11 we compare the observed frequencies of years with C's or A's when 4 A's or 4 C's, respectively, have occurred with the theoretical frequencies of such occurrences.

TABLE 11.—*Comparison of observed and theoretical frequencies of C's and A's in years that have exactly 4 A's or 4 C's, respectively*

| Number of C's in years with 4 A's | Observed frequencies | Chance frequencies | Number of A's in years with 4 C's | Observed frequencies | Chance frequencies |
|---|---|---|---|---|---|
| 0 | 22 | 21 | 0 | 28 | 25 |
| 1 | 21 | 20 | 1 | 18 | 22 |
| 2 or more | 8 | 10 | 2 or more | 12 | 11 |
| | 51 | 51 | | 58 | 58 |
| $\chi^2=0.498$, which with 2 degrees of freedom is not significant at the 10 percent level. | | | $\chi^2=1.178$, which with 2 degrees of freedom is not significant at the 10 percent level. | | |

These tests on randomness of C's and A's in a year indicate no tendency for them to occur with a frequency very much different from that which pure chance would allow.

## DISTRIBUTION OF PAIRS

The above comparisons test the tendency for persistence on a yearly basis; they would not very well indicate persistence of shorter periods. Therefore, probabilities of numbers of pairs were devised to give the chance probabilities of having two exceptionally wet months consecutively (A in one month followed by an A in the next) or of having two exceptionally dry months in succession (a C followed by a C). A frequency table of the number of pairs of extremely wet and extremely dry amounts at the 46 stations and 4 areas appears below with the corresponding chance frequencies. Because a $\chi^2$-test is considered to be less reliable if cell frequencies are less than 5, several numbers of pairs are grouped.

TABLE 12.—*Comparison of observed and theoretical frequencies of stations having various numbers of pairs of A's and C's*

| Pairs of A's | Observed number of stations | Chance frequencies | Pairs of C's | Observed number of stations | Chance frequencies |
|---|---|---|---|---|---|
| 0–3 | 7 | 6.4 | 0–3 | 5 | 6.4 |
| 4–5 | 17 | 15.3 | 4–5 | 8 | 15.3 |
| 6 | 8 | 8.8 | 6 | 6 | 8.8 |
| 7 | 7 | 7.6 | 7 | 7 | 7.6 |
| 8 or more | 11 | 11.9 | 8 | 6 | 5.4 |
| | 50 | 50.0 | 9 or more | 18 | 6.5 |
| | | | | 50 | 50.0 |
| This gave a value of 0.434 for $\chi^2$, which for 4 degrees of freedom is almost significant at the 99 percent level, indicating very close agreement with expected frequencies. | | | Here $\chi^2=25.09$ and with 5 degrees of freedom is significant at the 0.1 percent level. | | |

Mann and Wald [10] have recommended that for a more reliable $\chi^2$–test the theoretical frequencies of each class be as nearly equal as possible. Accordingly, the data in table 12 were regrouped as shown in table 13.

From the tests on the distribution of pairs of extremely wet and extremely dry precipitation amounts it is indicated that:

TABLE 13.—*Comparison of observed and theoretical frequencies of stations having various numbers of pairs of A's and C's*

| Pairs of A's | Observed number of stations | Chance frequencies | Pairs of C's | Observed number of stations | Chance frequencies |
|---|---|---|---|---|---|
| 0–5 | 24 | 21.7 | 0–5 | 13 | 21.7 |
| 6 or more | 26 | 28.3 | 6 or more | 37 | 28.3 |
| This resulted in 0.431 for $\chi^2$, which with 1 degree of freedom falls near the 50 percent level. | | | $\chi^2$ is now 6.17, which is almost significant at the 1 percent level with 1 degree of freedom. | | |

(1) Pairs of extremely wet amounts occur very much as would be expected by chance.

(2) Pairs of extremely dry amounts occur more often than chance frequency.

## CONCLUSIONS

1. Various tests indicate that in the United States the occurrence of pairs of extremely wet months is not significantly different from chance so far as the $\chi^2$-test can determine; however, the same tests indicate that pairs of extremely dry months occur more often than chance would predict.

2. The tests used indicate that the distribution of extremely wet and extremely dry months by years is not significantly different from chance in the United States—again subject to the limitations of the $\chi^2$-test.

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# THE WEATHER AND CIRCULATION OF MARCH 1951

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The most striking feature of the 700-mb. circulation during March 1951 (fig. 1) was the extensive area of positive height anomaly extending from middle latitudes in the Atlantic Ocean and eastern North America northwestward into the Canadian and Siberian Arctic and thence southward through the Bering Sea into the Pacific Ocean. The centers of +560 feet near the North Pole and +450 feet in the Davis Strait were the largest height anomalies in the entire Northern Hemisphere. At lower latitudes in the Atlantic there was a deep trough almost directly south of the abnormally strong ridge in Greenland and the northern Atlantic. This pattern of a ridge latitudinally superimposed over a trough, or positive height anomaly north of negative height anomaly, is characteristic of pronounced blocking action, where warm anticyclonic conditions prevail in subpolar regions and cold cyclonic conditions exist at lower latitudes. This blocking pattern was almost duplicated, with somewhat less intensity, over the east-central Pacific where the Aleutian-Bering Sea ridge with an anomaly of +330 feet was directly north of the deep trough (anomaly of −160 feet) west of the Hawaiian Islands. Most of these fea-

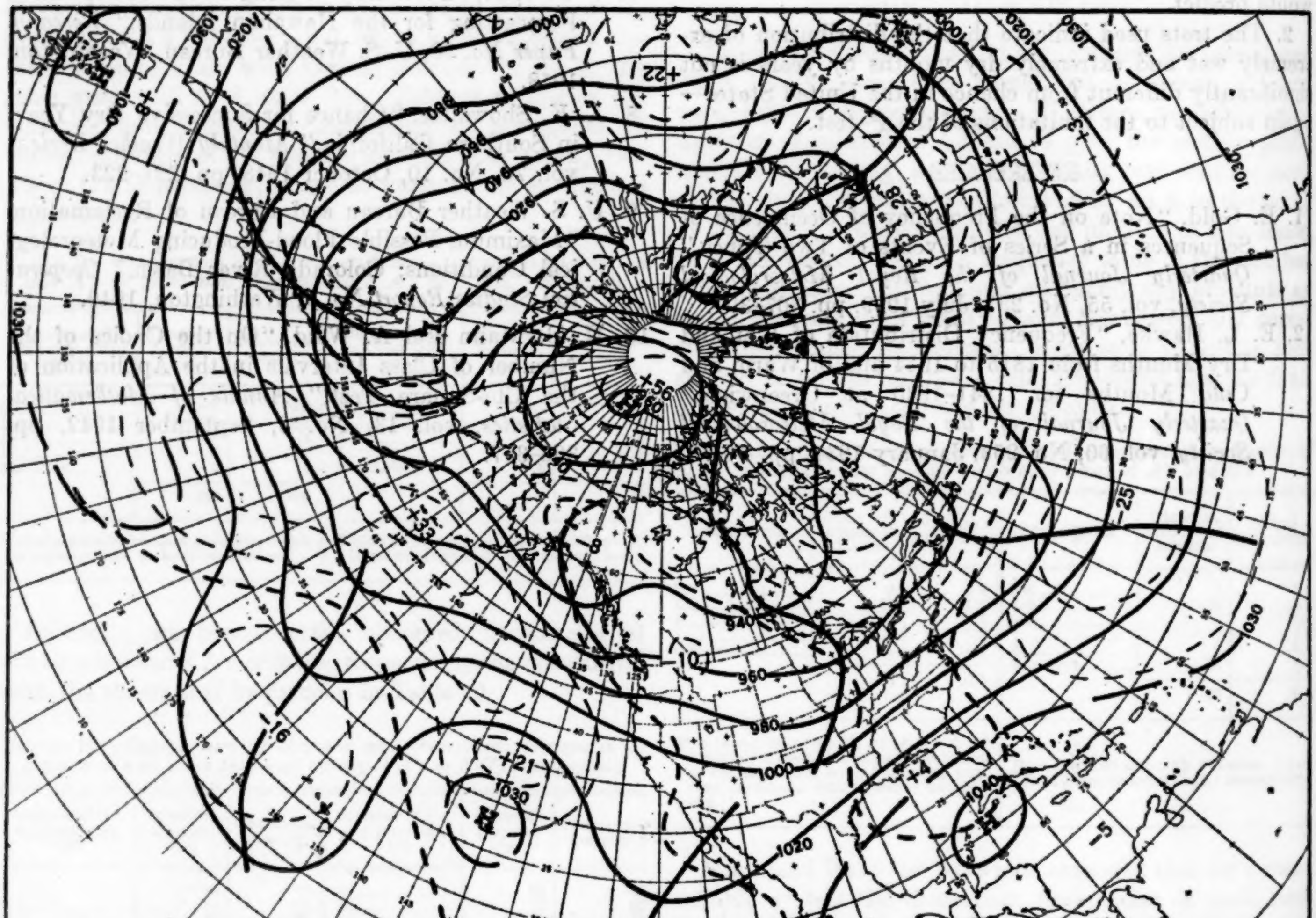

FIGURE 1.—Mean 700-mb. chart for the 30-day period February 27–March 28, 1951. Contours at 200-ft. intervals are shown by solid lines, intermediate contours by lines with long dashes, and 700-mb. height departures from normal at 100-ft. intervals by lines with short dashes with the zero isopleth heavier. Anomaly centers and contours are labeled in tens of feet. Minimum latitude trough locations are shown by heavy solid lines.

tures were also in evidence at sea level and higher levels (Charts XI–XV).[1] The pressure anomaly at sea level (Chart XI inset) was as striking as the 700-mb. anomaly with above normal pressures covering a vast area north of latitude 45°.

These patterns were associated with very weak westerlies in temperate latitudes in the Atlantic and Pacific. This is graphically illustrated in figure 2 where the average Western Hemisphere 700-mb. zonal wind speed profile for the month and the normal for March are shown. It is noteworthy that wind speeds in March 1951 were weaker than normal at all latitudes north of 25° N. except for the zone between 55° and 60° which was slightly above normal. In fact at about latitude 42°, where the westerlies normally have their peak speed in March, this month's speed was 4 m/sec below normal. Also, the maximum speed of the westerlies was located about 5° of latitude farther south than normal.

This sluggish nature of the westerlies during March 1951 was associated with a pronounced index cycle which lasted about five weeks from late February until late March. The index cycle, whose phases have been described by Rossby and Willett [1], is a period in which the temperate-latitude westerlies decline from comparatively high values to low values and then recover again. There are often relatively short-term fluctuations of this type, but Namias [2] has applied the term to cycles lasting several weeks. Namias pointed out the tendency for an index cycle to occur during late February and March in the period which he studied. The year 1951 was no exception to this rule as can be seen from the graph of the 5-day mean temperate-latitude 700-mb. zonal index shown in figure 3. Note how the westerly speed dropped from a peak of 12.7 m/sec (more than 2 m/sec above normal) on February 16 to a low of 4.6 m/sec (about 5 m/sec below normal) on March 12. Recovery soon followed as the index again climbed above the normal to reach a value of 11.1 m/sec on March 23.

A more complete picture of the nature of this index cycle is given by the 700-mb. wind speed time section in figure 4. This chart depicts the variation of the 5-day mean zonal wind speed in the Western Hemisphere with both latitude and time during February and March 1951. It is clear that the initial slowdown in the westerlies at middle latitudes occurred as the major westerly belt, which had been near latitude 45° early in February, gradually shifted northward after the first week of February reaching polar regions by the first week of March. Thus, by February 23 a minimum speed of only 4.5 m/sec was found at latitude 40°. A weak band of maximum westerlies was in evidence at lower latitudes as the main westerly stream progressed north of latitude 55° late in February. However, they remained weak until the disappearance of the fast westerlies at higher latitudes. Then as easterly winds dominated the subpolar regions,

[1] See Charts I–XV following p. 60 for analyzed Climatological Data for the month.

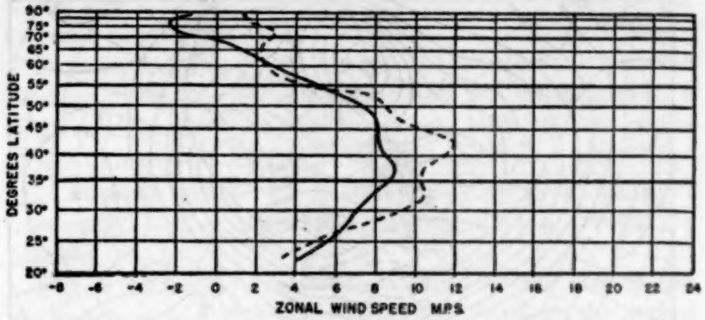


FIGURE 2.—Monthly mean 700-mb. geostrophic zonal wind speed profile in m/sec averaged from 0° westward to 180° longitude. Solid curve is for March 1951, dashed line is March normal.

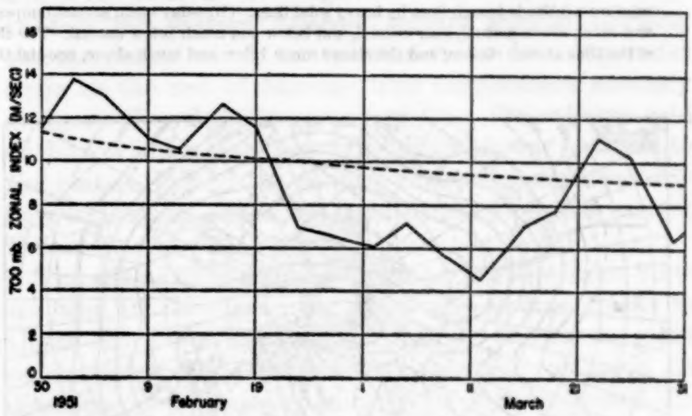


FIGURE 3.—Variation of temperate-latitude zonal index (average strength of zonal westerlies in m/sec between 35° N and 55° N.) at 700 mb. over the Northern Hemisphere from 0° westward to 180° longitude. Solid line connects 5-day mean zonal index values (plotted at middle of 5-day period) for February and March 1951. Dashed line shows variation of normal zonal index values for February and March.

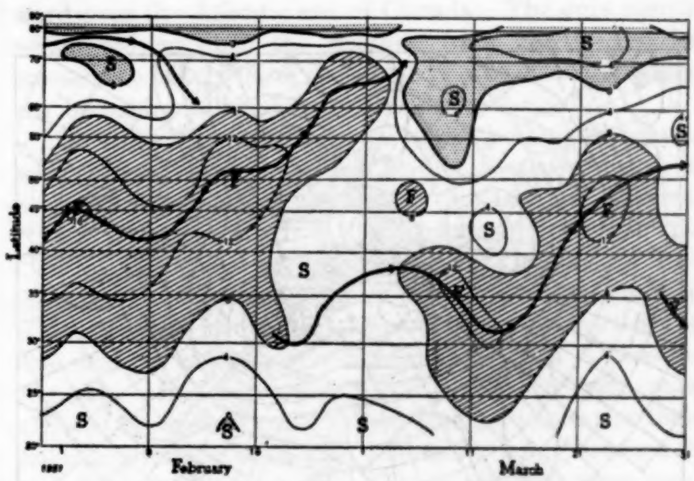


FIGURE 4.—Time-latitude section of 5-day mean zonal wind speed (averaged from 0° westward to 180° longitude) in m/sec at 700 mb. for February and March 1951. Isopleths are drawn at intervals of 4 m/sec. Areas with speeds greater than 8 m/sec are shaded with hatching; areas with negative speeds (easterlies) are shaded with dots. Maximum speed centers are labeled F, minima are labeled S. Heavy arrowed line marks latitudinal position of axis of maximum wind speed with time.

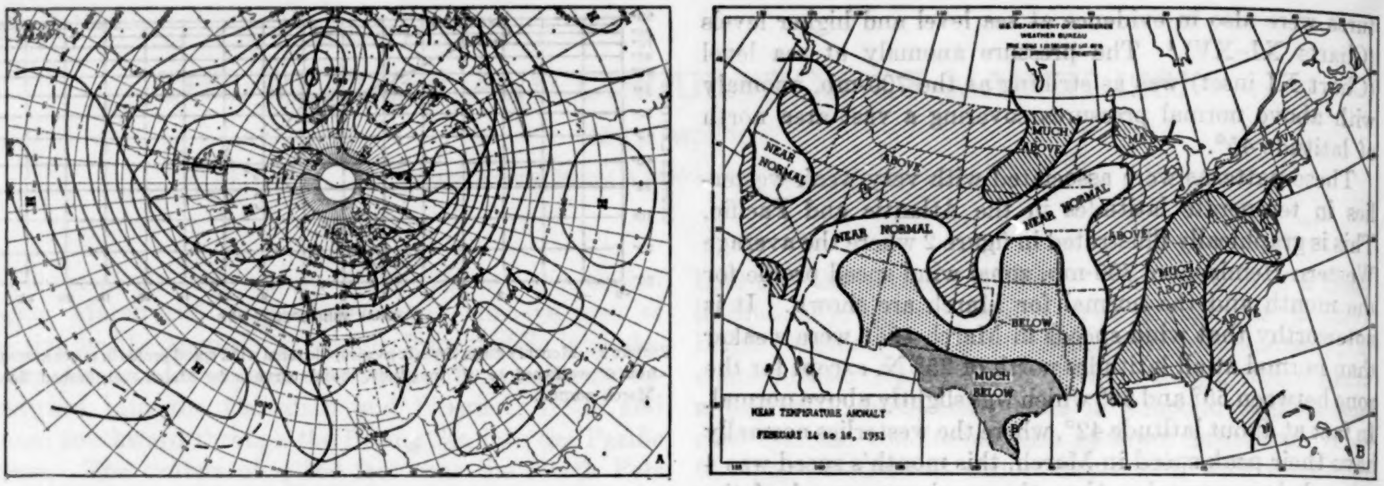


FIGURE 5.—(A) 5-day mean 700-mb. chart for period February 14–18, 1951. Contours at 200-ft. intervals are shown by solid lines, selected intermediate contours by dashed lines, and minimum latitude trough lines by heavy solid lines. (B) 5-day mean surface temperature anomaly over United States for period February 14–18, 1951 analyzed in terms of above and much above normal, near normal, and below and much below normal. The classes above, below, and near normal are so defined that they each normally occur one-fourth of the time at each station; and the classes much below and much above, one-eighth of the time.

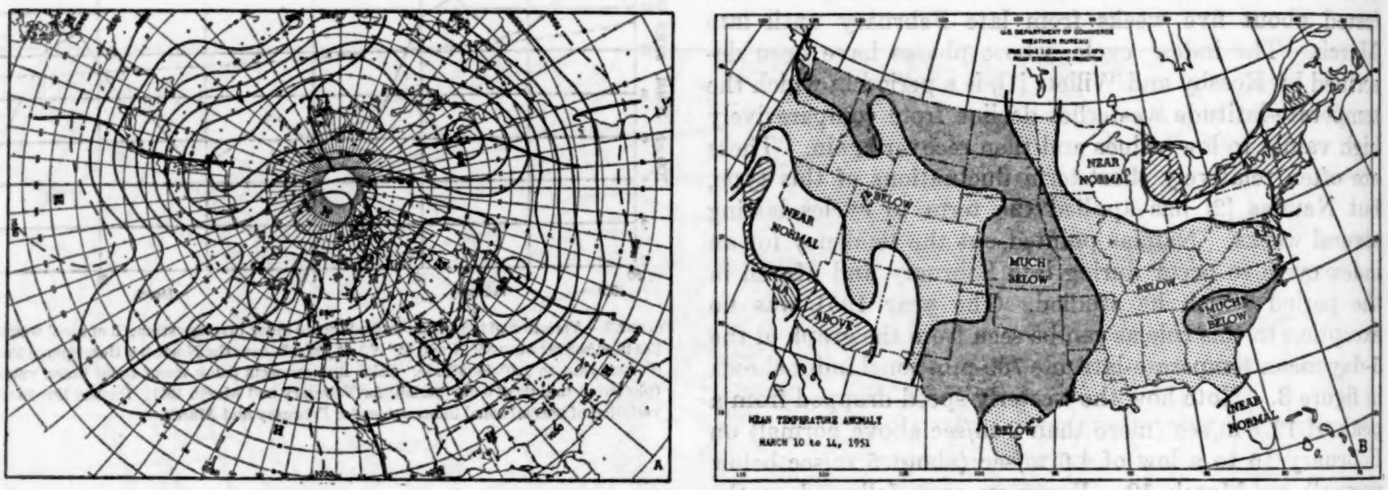


FIGURE 6.—(A) 5-day mean 700-mb. chart, March 10–14, 1951. (B) 5-day mean surface temperature anomaly over United States, March 10–14, 1951.

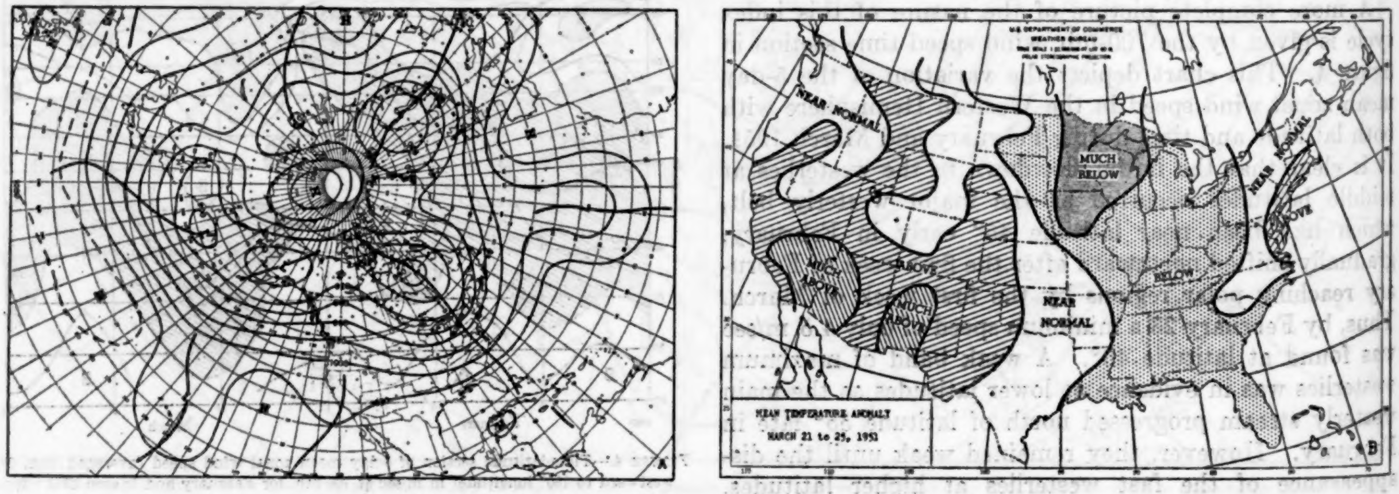


FIGURE 7.—(A) 5-day mean 700-mb. chart, March 21–25, 1951. (B) 5-day mean surface temperature anomaly over United States, March 21–25, 1951.

the lower latitude westerlies strengthened, reaching a peak of about 13 m/sec by March 10. These westerlies moved southward as far as latitude 32° by March 13, while the speed between latitudes 40° and 45° dropped to 3 m/sec. The westerlies then progressed northward again reaching a peak at latitude 45° by March 23. At the end of the month it appeared as though the westerlies were splitting once again and that another index cycle was beginning in April.

To illustrate the synoptic patterns associated with the various phases of this index cycle, three 5-day mean 700-mb. charts have been selected, and are shown in figures 5A, 6A, and 7A. Also, the corresponding 5-day mean surface temperature anomalies for the United States are presented in figures 5B, 6B, and 7B to demonstrate the temperature patterns associated with the phases of this cycle. Figure 5A shows the 700-mb. 5-day mean map centered at February 16, the high index point at the beginning of the cycle (figs. 3 and 4). Note the fast flat westerlies from the Pacific across Canada and out over the Atlantic with well-developed subtropical high cells to the south. Several low latitude troughs including a cut-off Low east of Bermuda and an easterly wave extending southwestward from the Hawaiian Islands were also present. As a result of this circulation pattern temperatures over the United States were predominantly on the warm side with below-normal temperatures only in portions of the South and Southwest (fig. 5B).

The extreme low index phase of the cycle, which occurred in the period centered at March 12 (figs. 3 and 4), is illustrated in figure 6A. Huge warm Highs dominated eastern Canada and the Canadian Arctic, while cold Lows were located along latitude 40° N. in the east-central Pacific, Illinois, and the western Atlantic. Deep cyclonic vortices were also located over the Gulf of Alaska and the British Isles. It is interesting to note that the lower latitude vortices and their associated troughs were located in approximately the same positions as the monthly mean troughs on the February 700-mb. chart [3] and the March chart (fig. 1). This indicates that low latitude cyclonic activity during an index cycle may be favored where pre-existing large-scale troughs (of the type found on a monthly mean chart) are located. It would seem quite natural that when fast westerlies deteriorate the cold polar air previously contained at high latitudes should drop southward into already established lower latitude troughs. Returning to figure 6A, it is seen that as a consequence of the low latitude cyclonic vortices there were pronounced westerlies in the subtropics, and the subtropical high cells in the Caribbean and the Atlantic were weak and displaced to the south. Turning now to figure 6B the effect of this low index circulation on temperature is immediately apparent. Temperatures were below, and much below, normal over almost the entire United States except in the Northeast, where warm oceanic easterly drift prevailed, and in the extreme Southwest.

It is interesting to note that the westerlies over the Eastern Hemisphere were strong and well-organized in a relatively simple wave pattern during both the low phase of the index cycle (fig. 6A) and the month as a whole (fig. 1). Thus, it would appear that the index cycle occurred over only the Western Hemisphere during February-March, 1951.

Figure 7A shows the 5-day mean 700-mb. circulation at the recovery point of the cycle (figs. 3 and 4), the period centered at March 23. The westerlies were once again organized in simple fashion at middle latitudes. The major vortex over North America had shifted northward to its more normal position near Hudson Bay. However, cut-off low latitude troughs still persisted near Hawaii and in the Atlantic (although now somewhat farther east). In fact the eastern Atlantic picture showed blocking characteristics which contributed to a lowering index again at the end of March. The temperature anomaly in figure 7B reflects the recovery from the extreme cold of the low index state (fig. 6B). Cold air was confined to the eastern half of the country under the northwesterly flow to the rear of the full-latitude trough in the eastern United States.

The effects of blocking action and the low index state are seen in the erratic nature of the cyclone tracks in Chart X. Note the frequent stalling of storms, rapid accelerations and decelerations, peculiar changes in direction, and frequent occurrence of motion toward the north and northwest. A notable example of this was the storm which started along the Gulf Coast on the 12th, traveled north-northeastward to Lake Ontario by the 15th, stalled for a day as it was blocked, and then accelerated rapidly toward the southeast into the region of the deep Atlantic trough (fig. 1). Blocking action was also responsible for the complete lack of storms moving eastward over the Atlantic out of Canada. The only storms which did go onto the Atlantic from North America crossed the east coast of the United States near the northern boundary of the lower latitude westerly belt.

The rather frequent cyclonic activity through central and eastern sections of the United States resulted in excessive precipitation in much of the East and Midwest (Chart III, A and B). The cyclogenetic area in the Central Plains east of the Continental Divide was associated with the stronger-than-normal thermal gradient (Chart I inset) in that region and the cyclonic vorticity in the trough extending northeastward from Oklahoma (fig. 1). Minnesota, Iowa, and Wisconsin were most affected by these storms. Much of the precipitation there fell in the form of snow with amounts totaling between 30 and 50 inches (Chart IV). These amounts were more than 400 percent of normal (Chart V-A) and even on March 27 (Chart V-B) there were still between 12 and

35 inches left on the ground. By the end of the month serious flooding in Iowa streams had begun as mild weather began melting the huge snow cover and copious rains added to the already excessive water supply on the ground.

The heavy precipitation in southern Texas (Chart III-B) was associated with the low latitude trough near Lower California and stronger-than-normal southerly flow off the Gulf of Mexico at sea level (Chart XI and inset). Much of the very heavy rainfall in Louisiana, Mississippi, and Alabama occurred with squall-line thundershowers in the closing days of the month as the major trough developed strongly in the eastern part of the country. (See article by Miller in this issue.)

Subnormal precipitation in the Southwest occurred under northwesterly flow aloft (fig. 1). The western Plains were also dry as somewhat stronger-than-normal northwesterly flow crossed the Divide. The dry area in Oklahoma and Arkansas is difficult to explain from the upper-level pattern. This area was located to the southeast of most of the cyclones (Chart X) and to the northwest of the squall line activity late in the month.

The average temperatures for March were below normal (Chart I and inset) throughout an extensive area of the United States from the Pacific Northwest to the Ohio Valley. The blocking ridge in the Atlantic and the accompanying westward displacement of the trough in Canada to the west of Hudson Bay (fig. 1) forced the cold polar outbreaks to drop into the United States quite far to the west. Chart IX shows that no anticyclones crossed from Canada into the United States east of North Dakota. The coldest area was the Northern Plains where temperatures averaged as much as 12° F. below the March normals (Chart I inset). Strong easterly continental drift of polar air at the surface (Chart XI and inset) contributed to this very cold weather in the Northern Plains and also to the cold conditions in the Pacific Northwest. It is not surprising then that cyclonic activity in the Northwest in the first 10 days (Chart X) resulted in snowfall which was very excessive for the area (Charts IV and V-A). This cyclonic activity was quite clearly associated with the trough in the northeast Pacific, the below normal heights in the area, and the stronger-than-normal northwesterly flow onto the Washington-Oregon coast (fig. 1).

The only area where temperatures were outstandingly above normal was in the Northeast where the strong easterly drift relative to normal associated with blocking caused a predominance of warm maritime flow into the region at both sea level (Chart XI inset) and aloft (fig. 1). The Southeast averaged just slightly on the above normal side even though the cold air swept into that area at and following the bottom of the index cycle (figs. 6B and 7B). However, extreme warmth early in the month while the subtropical ridge was well-developed led to the averages being slightly above the normal. This ridge (with heights just slightly above normal) was a feature of the monthly mean circulation (fig. 1).

The Hawaiian Islands received some of their heaviest rainfall on record in March 1951. Many stations on the Islands reported totals ranging from 200 to 700 percent of normal for the month. This was a result of the marked cyclonic activity associated with the deep low latitude trough to the west of Hawaii (fig. 1). As was mentioned earlier this trough was one of the major centers of action during the index cycle.

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2. J. Namias, "The Index Cycle and its Role in the General Circulation," *Journal of Meteorology*, vol. 7, No. 2, April 1950, pp. 130–139.
3. W. H. Klein, "The Weather and Circulation of February 1951," *Monthly Weather Review*, vol. 79, No. 2, February 1951, pp. 35–38.

# HEAVY RAINFALL IN MISSISSIPPI AND ALABAMA ON MARCH 27 TO 29, 1951

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## INTRODUCTION

The widespread, heavy rain that fell over much of the States adjacent to the Gulf of Mexico on March 27 and 28, was of unusual interest not only because of the flooding conditions that it helped initiate but also because the causes were not obvious from a cursory examination of the usual synoptic charts. The degree of convergence over the area could not be readily accounted for in terms of strong cyclonic flow, squall lines, frontal action, etc. Instability, augmented by cold air advection aloft or upslope motion, apparently was not an important factor since none of the available temperature soundings in the area yielded any supporting evidence of such activity. Although many factors appeared to play roles in the production of strong convergence and therefore abnormal precipitation, none seemed to be a primary influence.

## THE PRECIPITATION PATTERN

Above-normal 24-hour precipitation amounts were first reported on the morning of March 26 in southern Texas. The area covered on this day was small (approximately 30,000 square miles) in comparison to the size it subsequently reached and the maximum amount recorded at any point was only 1.7 in. By March 27, the area of abnormal precipitation amounts had doubled, covering eastern Texas, western Louisiana, and part of Arkansas. On March 28, the band of heavy rainfall had spread into Mississippi and Alabama and parts of surrounding States. The zone of maximum intensity lay through the center of Mississippi (fig. 1). On the following day (fig. 2) the maximum shifted eastward into central and northern Alabama. After March 29, the heavy precipitation area shrunk in size and decreased greatly in intensity but continued its slow eastward displacement.

The greatest intensity of precipitation occurred in Mississippi and Alabama resulting in widespread flooding in both States. In the former the maximum intensity was recorded at most locations near 0500 GMT of March 28, while in the latter it occurred approximately 24 hours later. A concept of the widespread nature of the heavy precipitation that occurred on these two days may be had from the number of counties in each State in which 24-hour amounts were exceedingly high. Of Mississippi's 81 counties, 22 contained stations reporting amounts at 1230 GMT on March 28 in excess of 3 in. Of those 22, at least

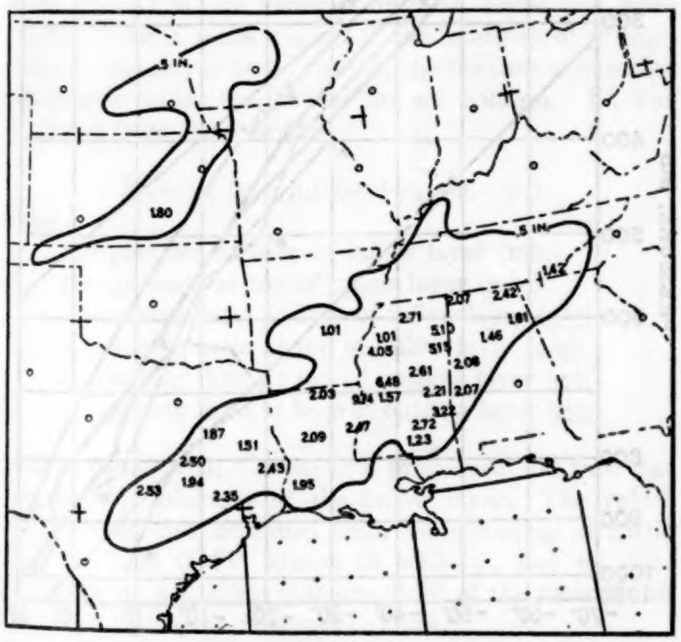

FIGURE 1.—24-hour rainfall reported at 1230 GMT on March 28, 1951. Solid lines delineate areas of 0.50 in. or more. Numbers indicate amounts in hundredths of an inch for "first-order" stations reporting 1.00 in. or more.

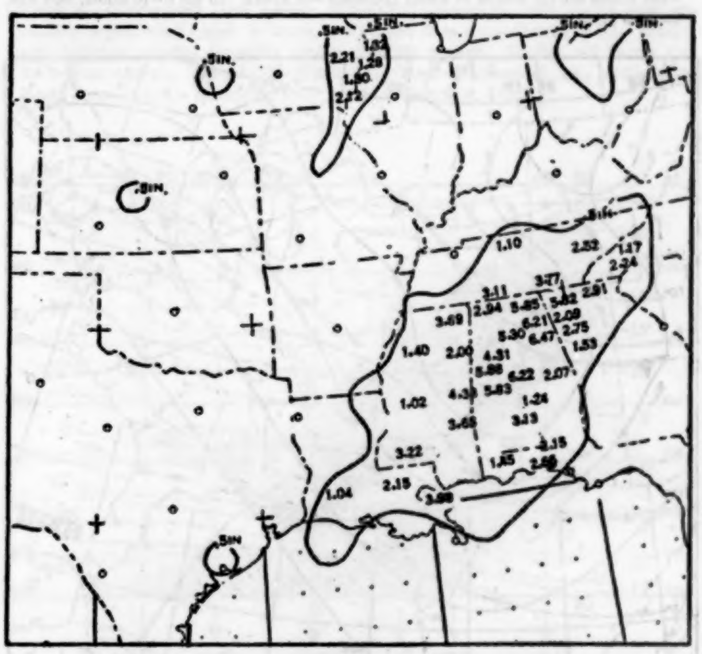

FIGURE 2.—24-hour rainfall reported at 1230 GMT on March 29, 1951.

11 contained reports of amounts greater than 5 in. In Alabama at 1230 GMT on March 29, there were reports in at least 27 of the State's 67 counties of amounts greater than 3 in. with 20 counties containing reports of over 5 in. One first-order station, Vicksburg, Miss., set a new record of 9.74 in. in 24 hours. The previous record, set on July 13, 1907, was 7.99 in.[1].

## MOISTURE SUPPLY

Considering the exceedingly heavy rainfall that occurred over a wide area, it is to be anticipated that there was present in the region ample moisture replenishment in addition to a mechanism for releasing the precipitation. That there was an abundant supply of moisture being advected into the region from the Gulf of Mexico is evident from the flow patterns that existed at most levels throughout the atmosphere (figs. 3, 4, and 8). The evolvement of the flow pattern of 0300 GMT, March 28, with its strong advection of moisture over the Gulf States, was very rapid. The large increase in humidity below 630 mb. in one day, illustrated by the 0300 GMT soundings of Little Rock, Ark., of March 27 and 28 (fig. 5), is evidence of the rapidity with which the strong southerly flow developed. Until 0300 GMT, March 26, most of the southern States were dominated by northwest winds at most levels in the atmosphere, but within 24 hours, the entire region was covered by southerly winds which increased rapidly in speed immediately after the shift in direction. This sudden change was brought about by the approach of an intensifying trough from the west. The trough, which originated with a cold incursion from the Pacific Ocean and intensified only slightly during its passage over the Rockies, strengthened abruptly as it moved into the Plains on March 27.

Some idea of the replenishment rate required to produce rainfall of the magnitude reported over a wide area can be obtained from the simple calculations demonstrated by Showalter [2]. Taking the sounding of 0300 GMT, March 28, at Little Rock, Ark., to be representative of

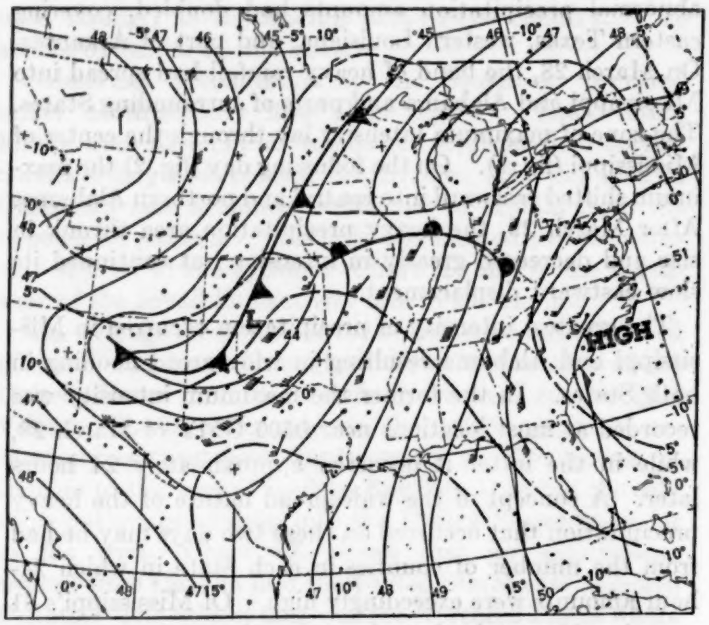


FIGURE 3.—850-mb. chart for 0300 GMT, March 28, 1951. Contours (solid lines) at 100-ft. intervals are labeled in hundreds of geopotential feet. Isotherms (dashed lines) are at intervals of 5° C. Lines of equal dew point (dotted) are at intervals of 10°C. Barbs on wind shafts are for speeds in knots (pennant=50 knots, full barb=10 knots, and half barb=5 knots).

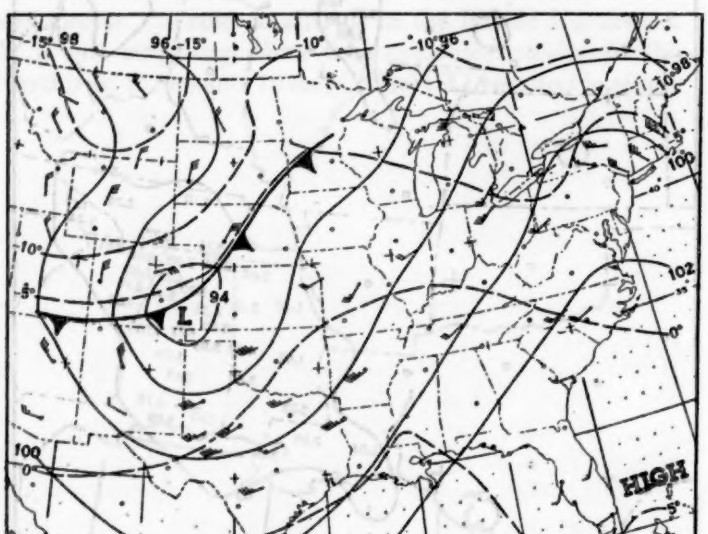


FIGURE 4.—700-mb. chart for 0300 GMT, March 28, 1951. Contours are at 200-ft. intervals.

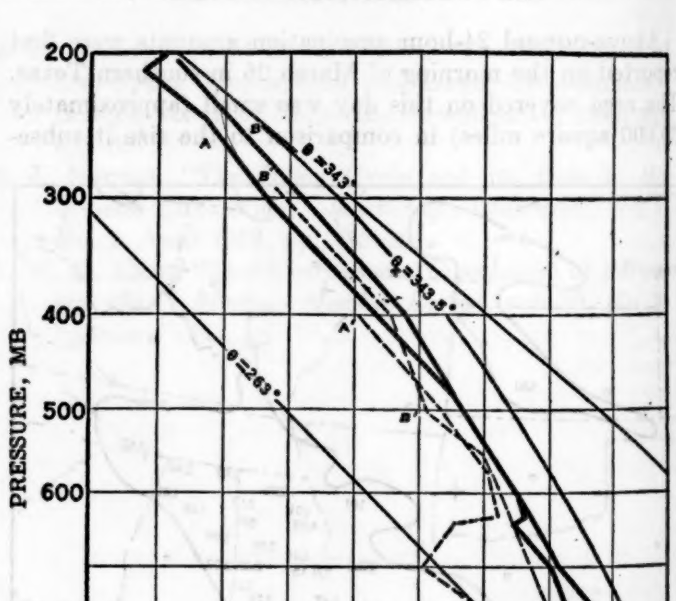


FIGURE 5.—Radiosonde observations at Little Rock, Ark., for 0300 GMT. Curves A and A′ denote temperature and dew point, respectively, for March 27, 1951, while curves B and B′ are for March 28, 1951.

humidity conditions within the area of abnormal precipitation, and by using Showalter's procedure of summing the moisture content over 50-mb. increments, the amount of precipitable water content in the layer from 1000 mb. to 700 mb. was found to be 0.92 in. If complete convection of this 300-mb.-thick layer were to take place so that all water were removed, in order to deposit 5.5 in. of precipitation in a day over a 50-mile-wide zone, a mean inflow of 12.5 mph would be required (5.5 in.×50 miles/0.92 in.×24 hours). If only one third of the precipitable water (0.30 in.) were removed across this same zone then replenishment would have to be at the mean rate (wind speed) of about 38 mph. If a drier layer such as that between 700 mb. and 400 mb. were the convecting layer then the replenishment rate would necessarily be even greater. An increase in the width of the zone of precipitation would result in the requirement of higher wind velocities. It can be seen from these values that, for heavy precipitation over a wide area and long periods of time, in addition to strong advection of moist air intense convergence would be necessary to bring about sufficient upward motion of the air.

## PRECIPITATION MECHANISM

Some concept of the average minimum amount of convergence that occurred in the vicinity of the heavy rainfall may be obtained from Showalter's formula [2], wherein he assumes that the velocity drop across a rainfall basin is representative of the amount of air being forced to convect:

$$I=\frac{W_e(v_i-v_o)}{Y}$$

where $(v_i-v_o)$ is the velocity drop in miles per hour across a basin $Y$ miles wide, $I$ is the intensity of precipitation in inches per hour, and $W_e$ the maximum effective precipitable water (inches) in the air column. $W_e$ was computed from the formula:

$$W_e=0.2\ (p_0-p_1)\ (w_0+w_1-w_2-w_b)$$

where,

$p_0$=pressure at base of inflow layer (mb.)
$p_1$=pressure at top of inflow layer (mb.)
$w_0$=mixing ratio at base of inflow layer (g/g)
$w_1$=mixing ratio at top of inflow layer (g/g)
$w_2$=mixing ratio at top of outflow layer (g/g)
$w_b$=mixing ratio at base of outflow layer (g/g)

In accordance with Showalter's procedure 300 mb. was used for the thickness of the inflow layer. The values of $w_0$ and $w_1$ were obtained from the sounding at Little Rock for 0300 GMT, March 28 while $w_2$ and $w_b$ were calculated by assuming that one-third of the moisture of the inflow layer was removed. Thus,

$$W_e=0.2\ (300)\ [0.0110+0.0045-\tfrac{2}{3}\ (0.0110+0.0045)]$$
$$=0.31\ in.$$

Inserting in the first equation the conservative values of 50 miles for $Y$, 0.2 in./hour (4.8 in./day) for $I$, and 0.31 in. for $W_e$ derived above, and solving for $(v_i-v_o)$, a velocity drop of approximately 31 mph/50 miles was found.

That such a velocity drop probably existed and may have been far exceeded for short periods of time and over fairly large areas [1] during the occurrence of the heavy rainfall may be inferred from the vertical cross sections of figures 6 and 7 for 0300 GMT, March 27, and 0300 GMT, March 28, respectively. They have been drawn so as to lie approximately parallel to the mean flow direction between 850 mb. and 300 mb. At the same time they skirt the northern edge of the maximum precipitation

[1] Short-duration horizontal convergence over small areas sometimes reaches enormous values. As Byers and Braham [3] point out, values of convergence in the vicinity of micro-lows forming along squall lines could exceed 20/hr.

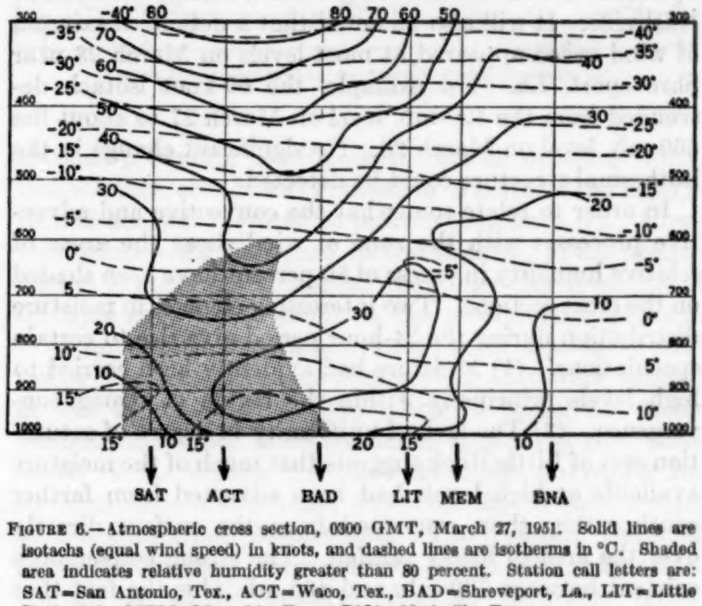


FIGURE 6.—Atmospheric cross section, 0300 GMT, March 27, 1951. Solid lines are isotachs (equal wind speed) in knots, and dashed lines are isotherms in °C. Shaded area indicates relative humidity greater than 80 percent. Station call letters are: SAT=San Antonio, Tex., ACT=Waco, Tex., BAD=Shreveport, La., LIT=Little Rock, Ark., MEM=Memphis, Tenn., BNA=Nashville, Tenn.

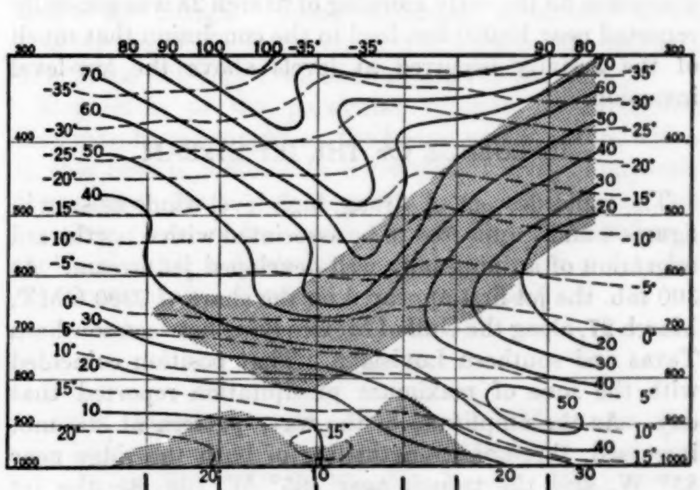


FIGURE 7.—Atmospheric cross section, 0300 GMT, March 28, 1951.

area. The gradient of the lines of equal wind speed (isotachs) give some indication of the existing convergence. It can be seen that on March 28 there existed between Little Rock, Ark., and Nashville, Tenn., a distance of approximately 300 miles, a mean gradient of speed of more than 30 knots in the layer 700-400 mb. A maximum of gradient of 50 knots existed at the 540-mb. level. Contrast the isotach pattern of March 28 with that which existed in the same layer on the previous day. The mean gradient in the layer on March 27 was less than 12 knots. Since the winds aloft observation at Memphis on March 28 was missing it was necessary to draw as even a gradient between Little Rock and Nashville as the available data permitted. It is thus possible that an even stronger gradient than shown existed at some points between the two stations. It is noteworthy that, despite the large increase in speed in the 700–400 mb. layer that occurred upstream from Nashville, only a small change occurred at Nashville. It will also be noted that a definite maximum of wind speed appeared at most levels on March 28 near Shreveport, La. For example, the 60-knot isotach descended from the 420-mb. level on March 27 to about the 660-mb. level on March 28. No significant change in the isothermal structure could be detected.

In order to relate somewhat the convective and advective processes with the zone of wind shear the areas of relative humidity in excess of 80 percent have been shaded on the cross sections. Two interesting changes in moisture distribution during the 24-hour period give rise to certain speculations. (1) Moisture had evidently been carried to high levels principally within the region of strong convergence. (2) The lack of uniformity in degree of saturation east of Little Rock suggests that much of the moisture available at high levels had been advected from farther south rather than convected from the surface directly over the area of heavy rainfall. The strong convergence existent between 700 mb. and 400 mb. plus the fact that the base of the upper deck of clouds over the area under discussion on the early morning of March 28 was generally reported near 10,000 feet lead to the conclusion that much of the activity occurred at levels above the low-level inversion.

## INFLUENCE OF THE JET STREAM

The rapid descent of strong, high-level winds as seen in figures 6 and 7 appeared to be associated with a northward migration of an unusually well-developed jet stream. At 300 mb. the jet first appeared on the chart of 0300 GMT, March 27, along the Gulf of Mexico lying between southern Texas and southern Louisiana. That position coincided with the zone of maximum precipitation reported that day. As the amplitude of the wave pattern at 300 mb. increased, through strengthening of both the ridge near 85° W. and the trough near 105° W. (fig. 8), the jet migrated northward to the position over northwestern Louisiana shown at 0300 GMT, March 28.

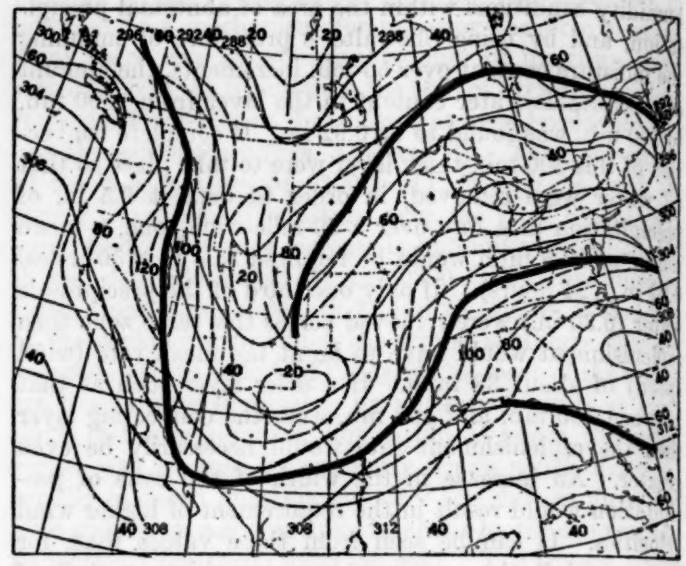

FIGURE 8.—300-mb. chart for 0300 GMT, March 28, 1951. Contours (solid lines) at 400-ft. intervals are labeled in hundreds of geopotential feet. Dashed lines represent isotachs (equal wind speed) and are at intervals of 20 knots. Heavy line represents jet stream.

Although the vertical motion existing in the vicinity of a jet is as yet little understood it was strikingly coincidental that such a well-developed jet [2] moved directly over the region of heavy rainfall near the time of maximum intensity. The model of vertical motion postulated by the University of Chicago [4] calls for sinking, southward motion in the upper troposphere to the south of the jet at 300 mb. and ascending, northward motion below it. Starrett [5] in his investigation of 57 synoptic situations, showed that maxima of precipitation generally occur under the jet at 300 mb. with a standard deviation of maxima of approximately 5° latitude. He also found that where the west wind component of the jet exceeded 50 mps (97 knots) relatively heavier precipitation would occur than where a lesser speed existed. Winds greater than 100 knots were actually reported in this case.

## SURFACE AND CONSTANT-PRESSURE CHARTS IN RELATION TO PRECIPITATION

There were several characteristics of the surface and upper-level charts that were indicative of convergence with resulting precipitation. However, none appeared with sufficient intensity nor was coincident with the time of the maximum rainfall. The strong southerly flow of maritime tropical air from the Gulf of Mexico probably produced within itself horizontal convergence as it moved toward northerly latitudes. There was also present in the lower levels (figs. 3 and 4) over the region slight cyclonic curvature of the contours which is conducive to convergence [6]. Another effect to be considered was the presence of a diffuse warm front (figs. 9, 10, and 11) but most of the intense rainfall occurred south of it.

[2] There was an actual reported velocity of 170 knots within the jet at 200 mb.

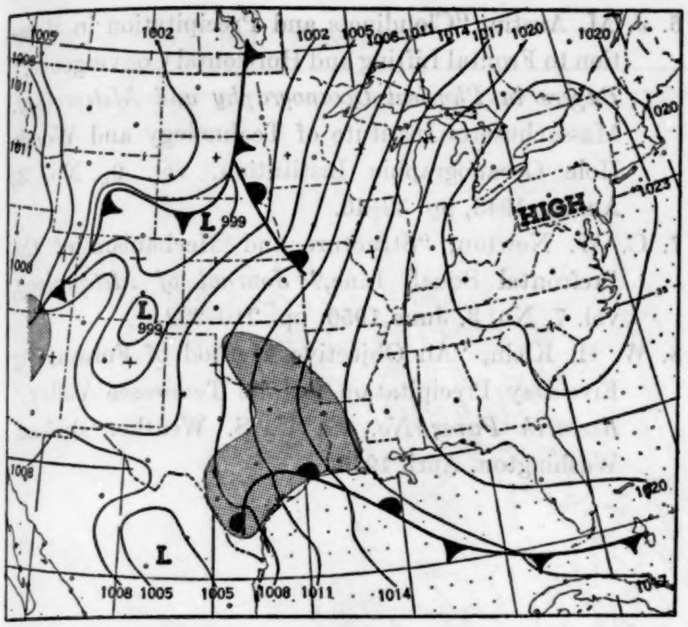


FIGURE 9.—Surface weather chart for 0030 GMT, March 27, 1951. Shading indicates areas of active precipitation.

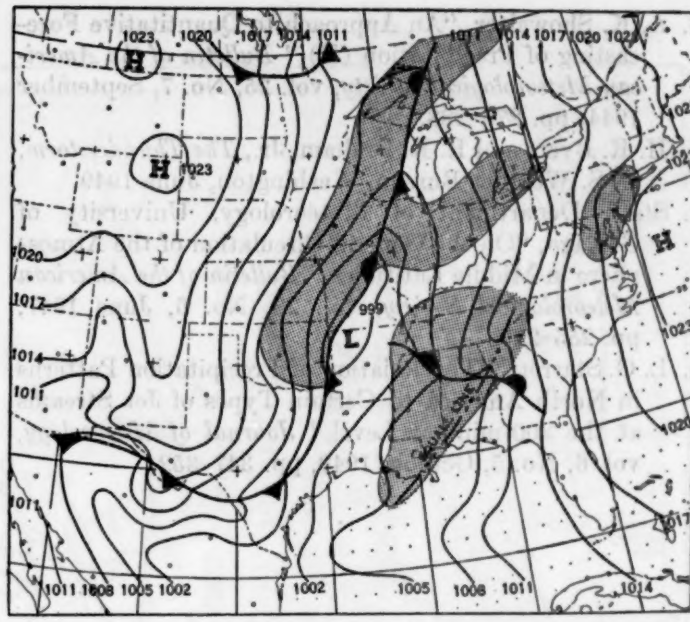


FIGURE 11.—Surface weather chart for 0030 GMT, March 29, 1951.

There was no indication of increasing instability during the 24-hour period prior to the time of maximum precipitation. No advection of cold air was discernible from an examination of either the constant-pressure charts or individual soundings in the area. The soundings at Little Rock (fig. 5) illustrate the small changes that occurred over most of the region.

Since most of the precipitation fell during thunderstorms it might be suspected that squall lines played an important role. In the absence of a dense network of stations providing continuous records of pressure, wind, temperature, etc., it was impossible to perform the highly-refined analysis required to locate squall lines [7]. However, considering the broad east-west extent of the precipitation area, it would appear that only the presence of multiple squall lines could fit the precipitation pattern.

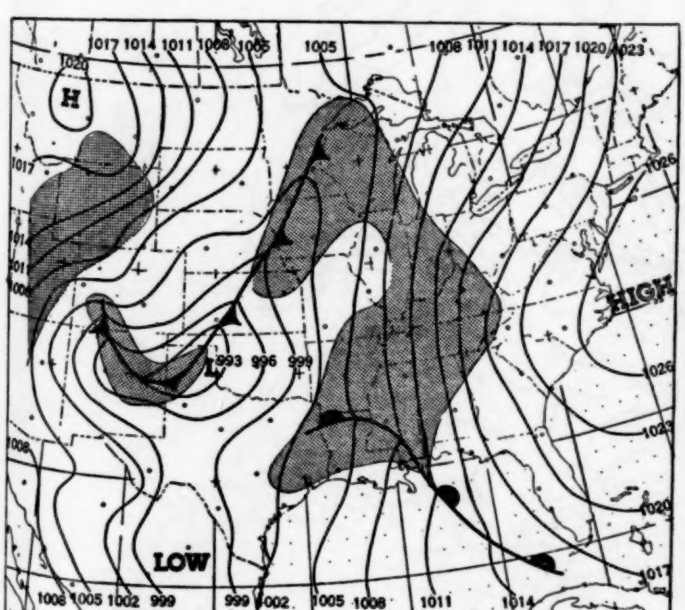


FIGURE 10.—Surface weather chart for 0030 GMT, March 28, 1951.

As for statistical parameters commonly associated with heavy precipitation there were several that were verified in this case. For example, Klein [8] found for 5-day periods that heavy precipitation is typical of the zone ahead of the trough and that the optimum region for its occurrence is about half way from the 700-mb. trough to the first ridge downstream. The 700-mb. chart of figure 4 presents a wave pattern which fulfills those requirements almost exactly. Another favorable factor of the 700-mb. chart is the northeast-southwest orientation of the trough. Strong confluence, considered favorable for heavy precipitation, is indicated by the 850-mb. flow but is not very evident from the 700-mb. chart.

Regardless of the particular synoptic characteristic that may have brought on the heavy precipitation, which in this case is difficult to determine, strong, large-scale convergence must have been present. The mechanism creating these wide areas of convergence remains a problem which is likely to be solved only by a detailed examination of a dense network of stations.

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4. Staff, Department of Meteorology, University of Chicago, "On the General Circulation of the Atmosphere in Middle Latitudes," *Bulletin of the American Meteorological Society*, vol. 28, No. 6, June 1947, pp. 255-280.
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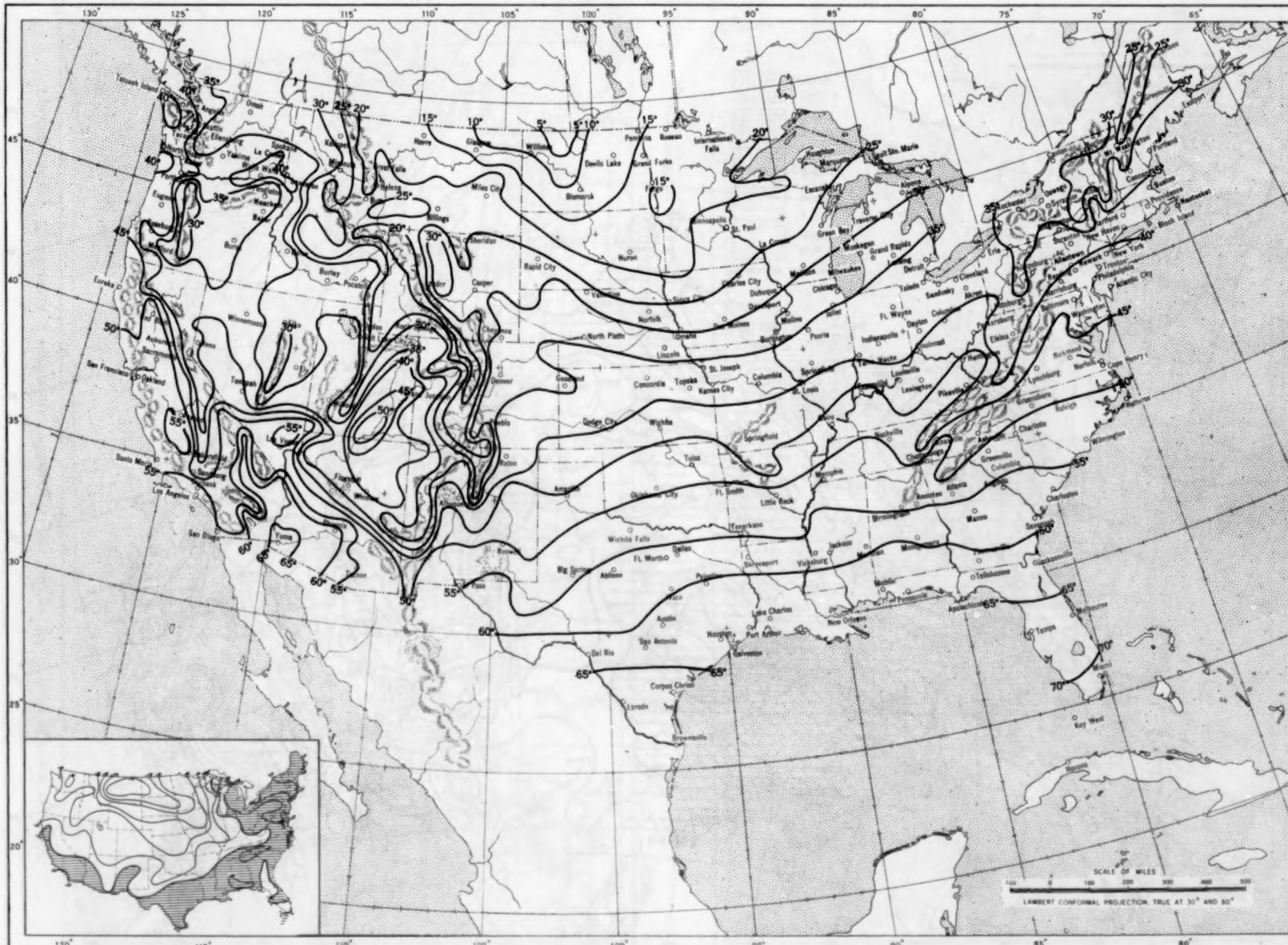
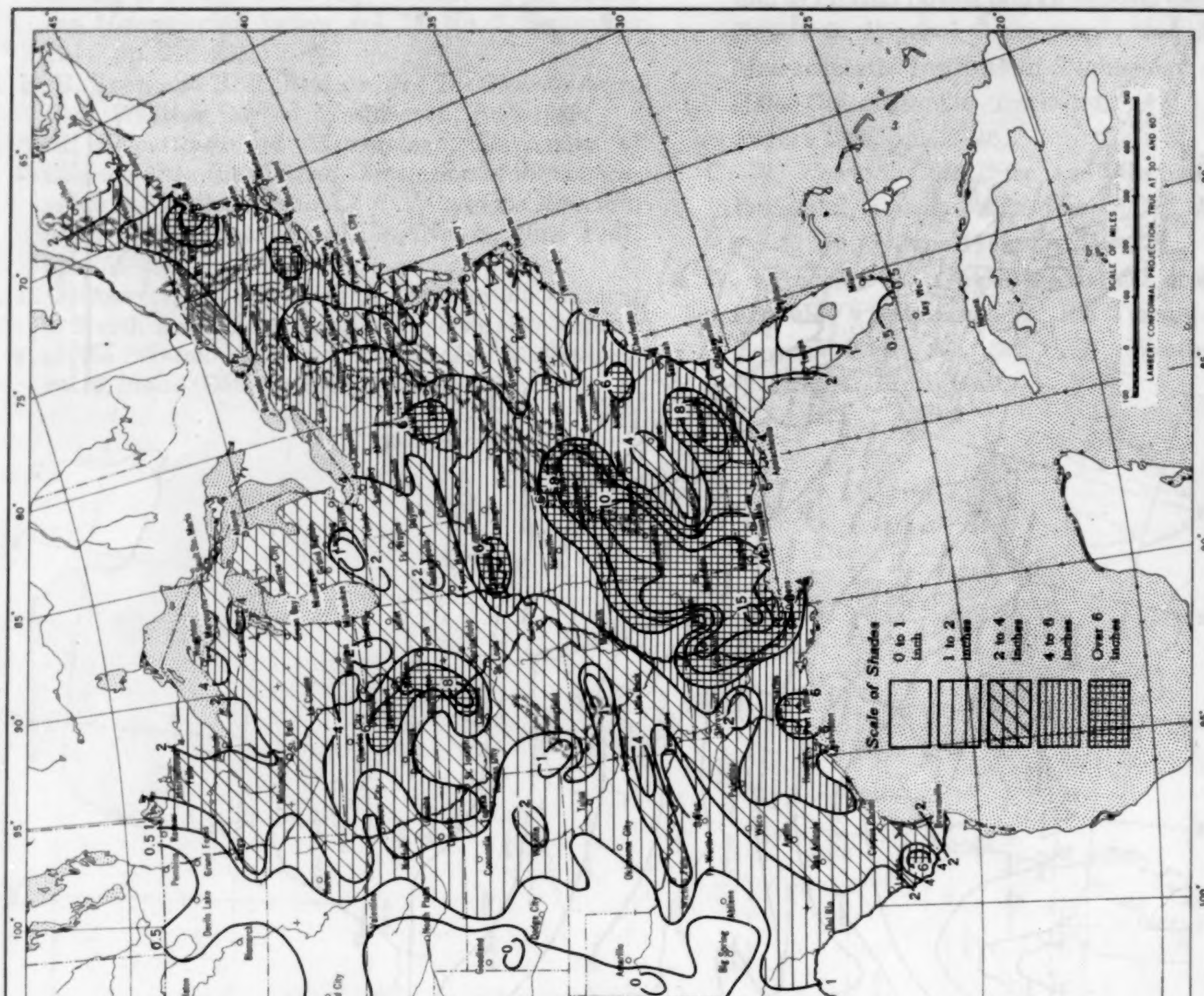
Chart I. Average Temperature (°F.) at Surface, March 1951. Inset: Departure of Average Temperature from Normal (°F.), March 1951.



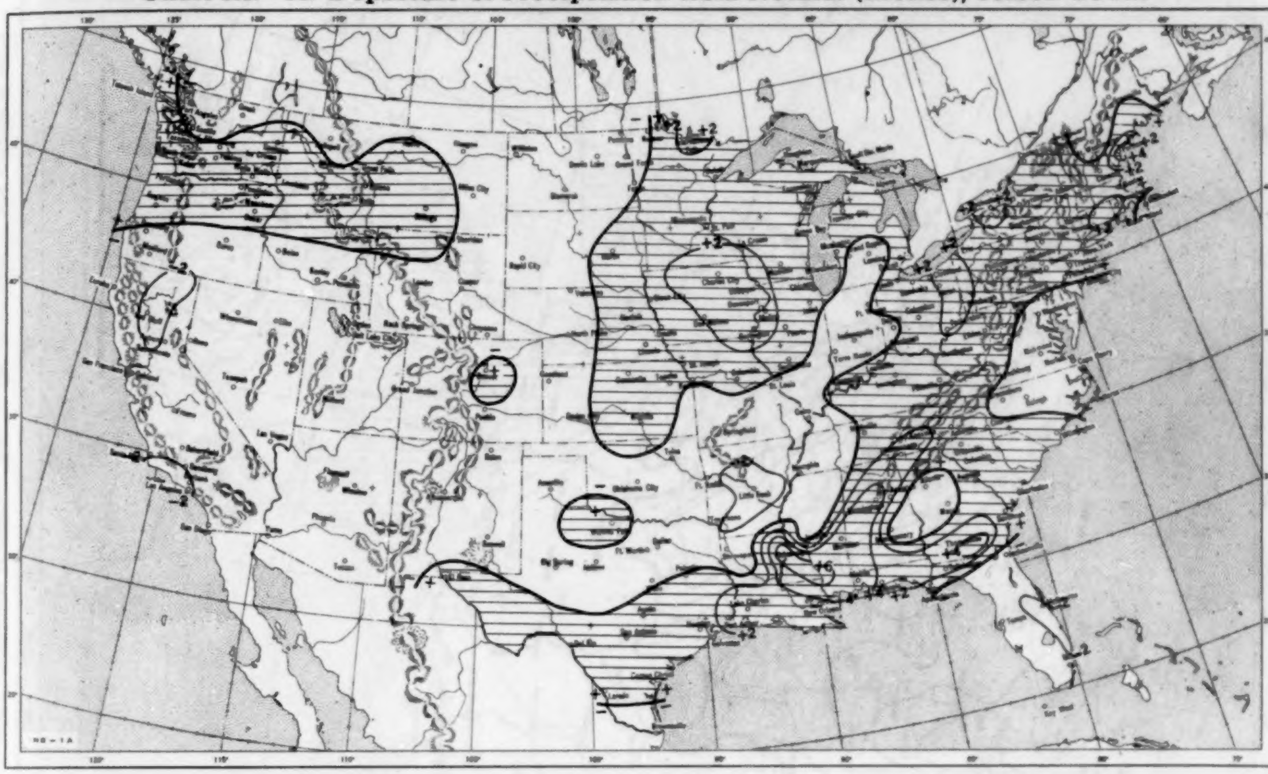

Based on reports from 800 Weather Bureau and cooperative stations. The monthly average is half the sum of the monthly average maximum and monthly average minimum, which are the average of the daily maxima and daily minima, respectively. Normal average monthly temperatures are computed for Weather Bureau stations having at least 10 years of record.

Chart II. Total Precipitation (Inches), March 1951.

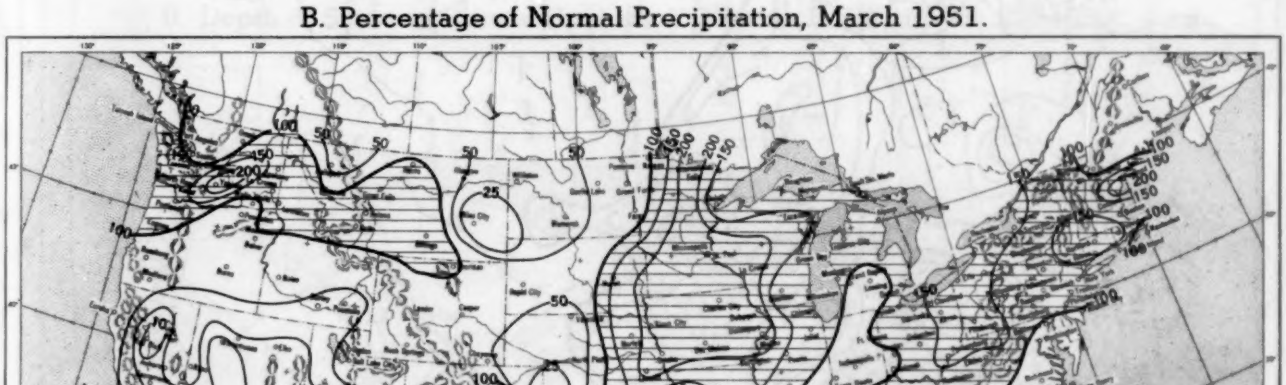



Based on daily precipitation records at 800 Weather Bureau and cooperative stations.

Chart III. A. Departure of Precipitation from Normal (Inches), March 1951.

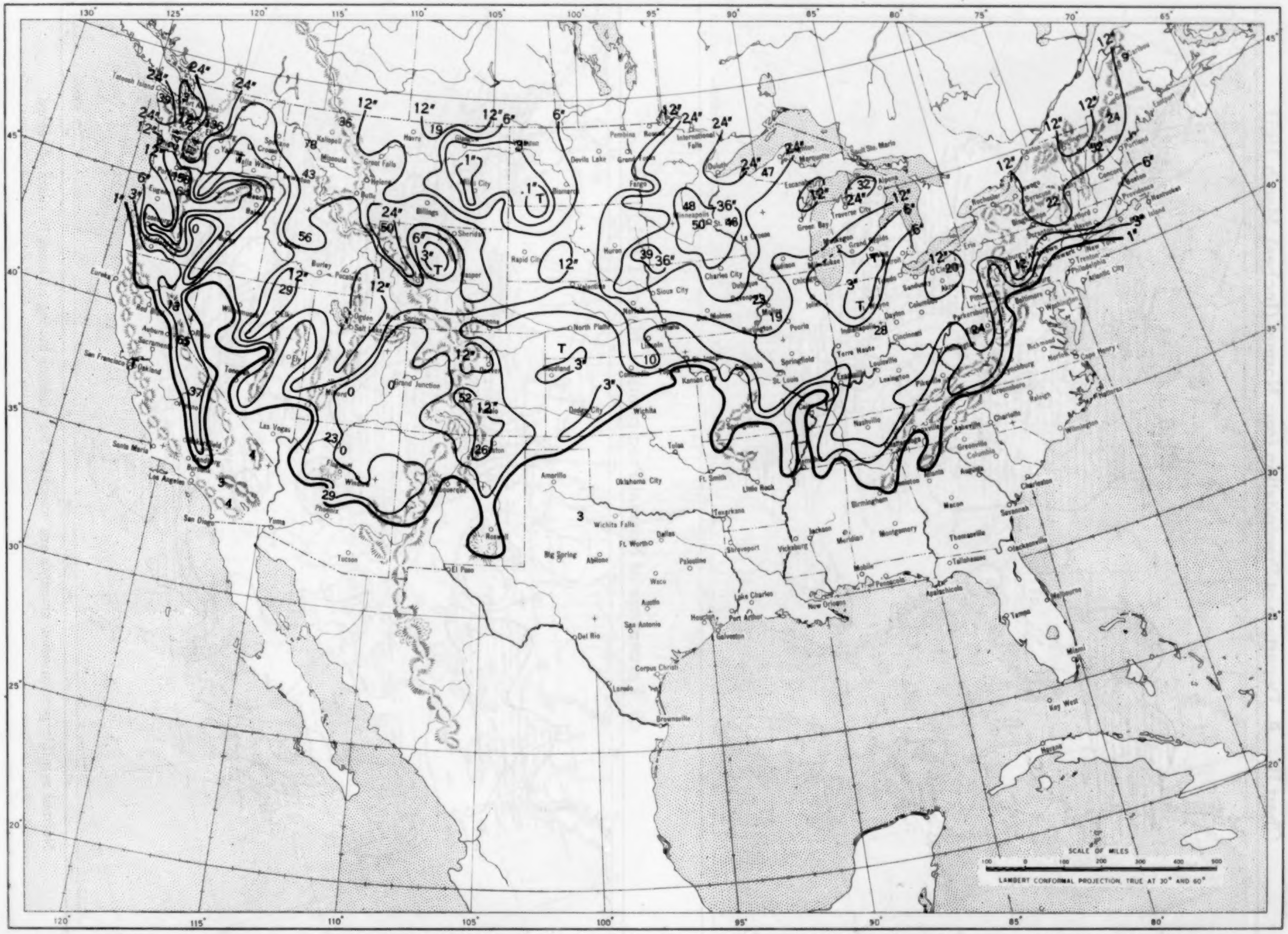


B. Percentage of Normal Precipitation, March 1951.



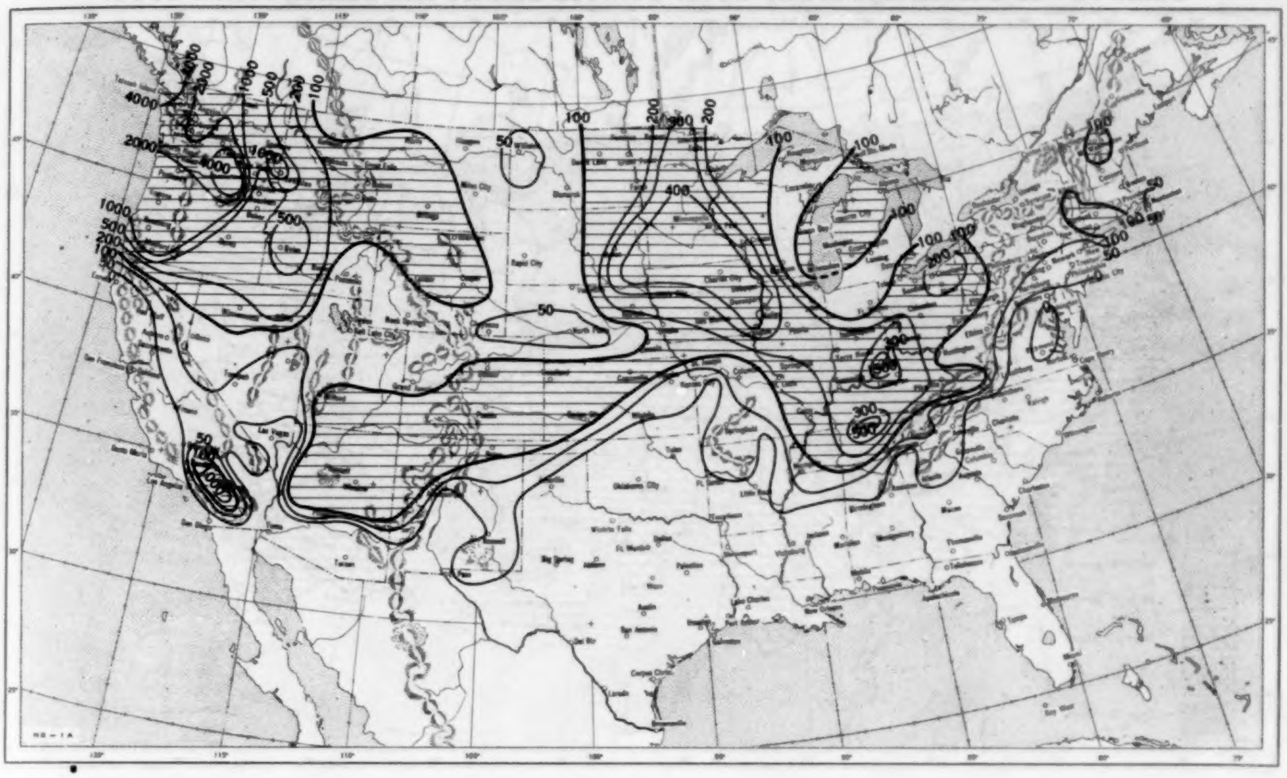
Normal monthly precipitation amounts are computed for stations having at least 10 years of record.

Chart IV. Total Snowfall (Inches), March 1951.

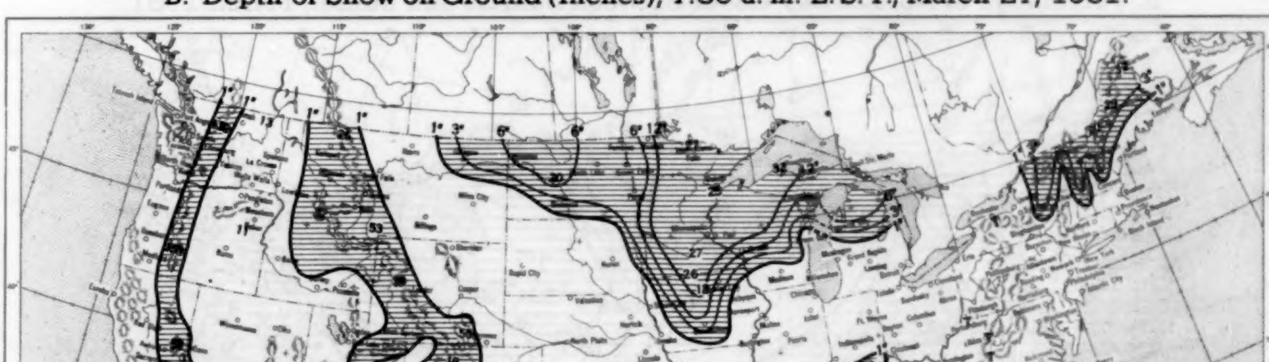



This is the total of unmelted snowfall recorded during the month at Weather Bureau and cooperative stations. This chart and Chart V are published only for the months of November through April although of course there is some snow at higher elevations, particularly in the far West, earlier and later in the year.

## Chart V. A. Percentage of Normal Snowfall, March 1951.

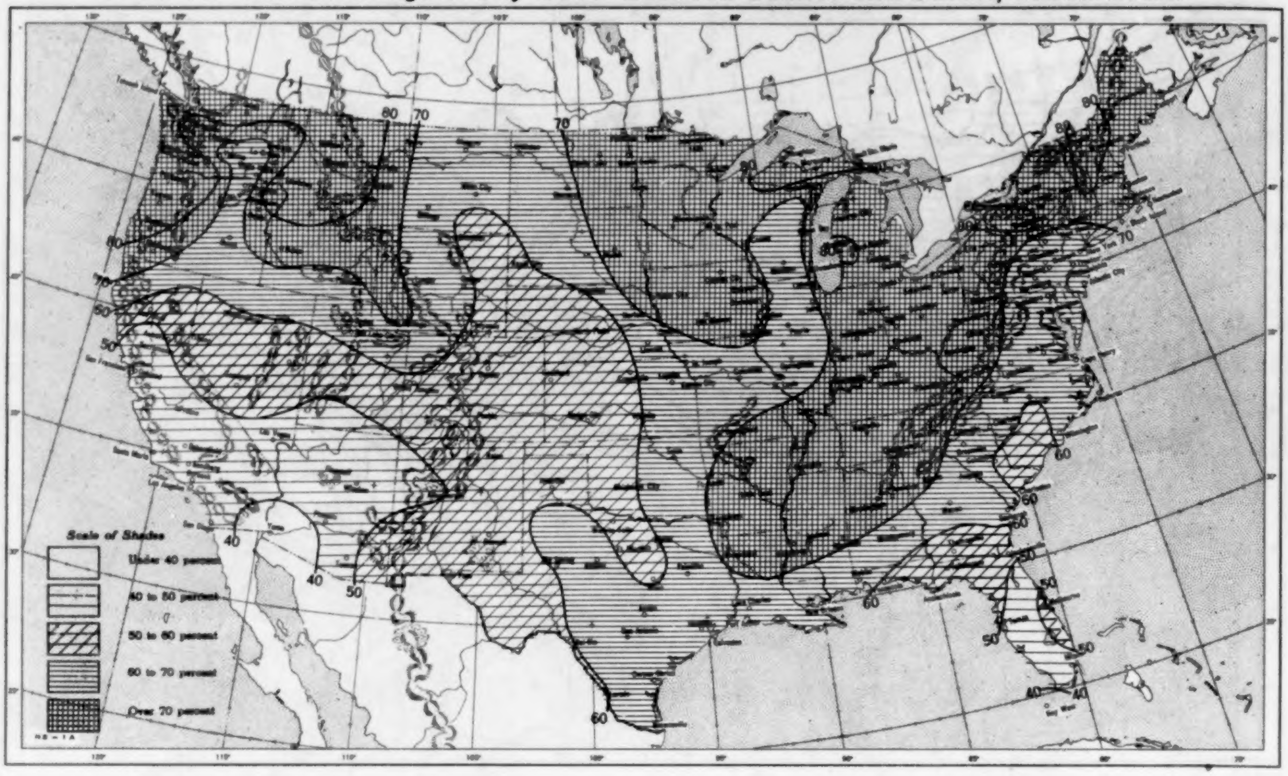


## B. Depth of Snow on Ground (Inches), 7:30 a. m. E. S. T., March 27, 1951.

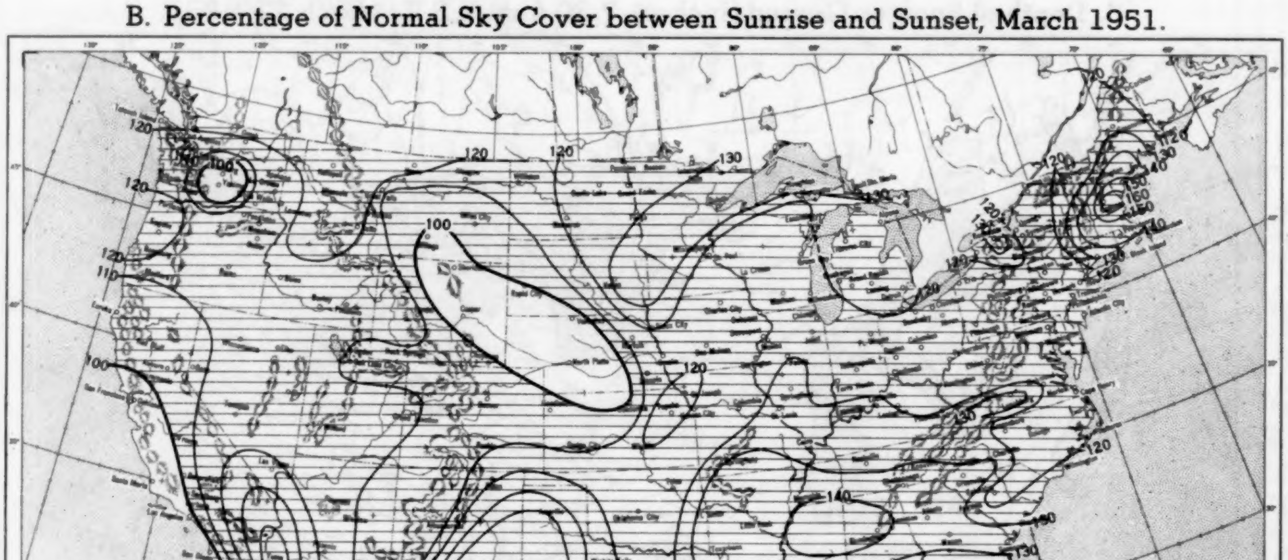


A. Amount of normal monthly snowfall is computed for Weather Bureau stations having at least 10 years of record.
B. Shows depth currently on ground at 7:30 a. m. E. S. T., of the Tuesday nearest the end of the month. It is based on reports from Weather Bureau and cooperative stations. Dashed line shows greatest southern extent of snowcover during month.

## Chart VI. A. Percentage of Sky Cover Between Sunrise and Sunset, March 1951.

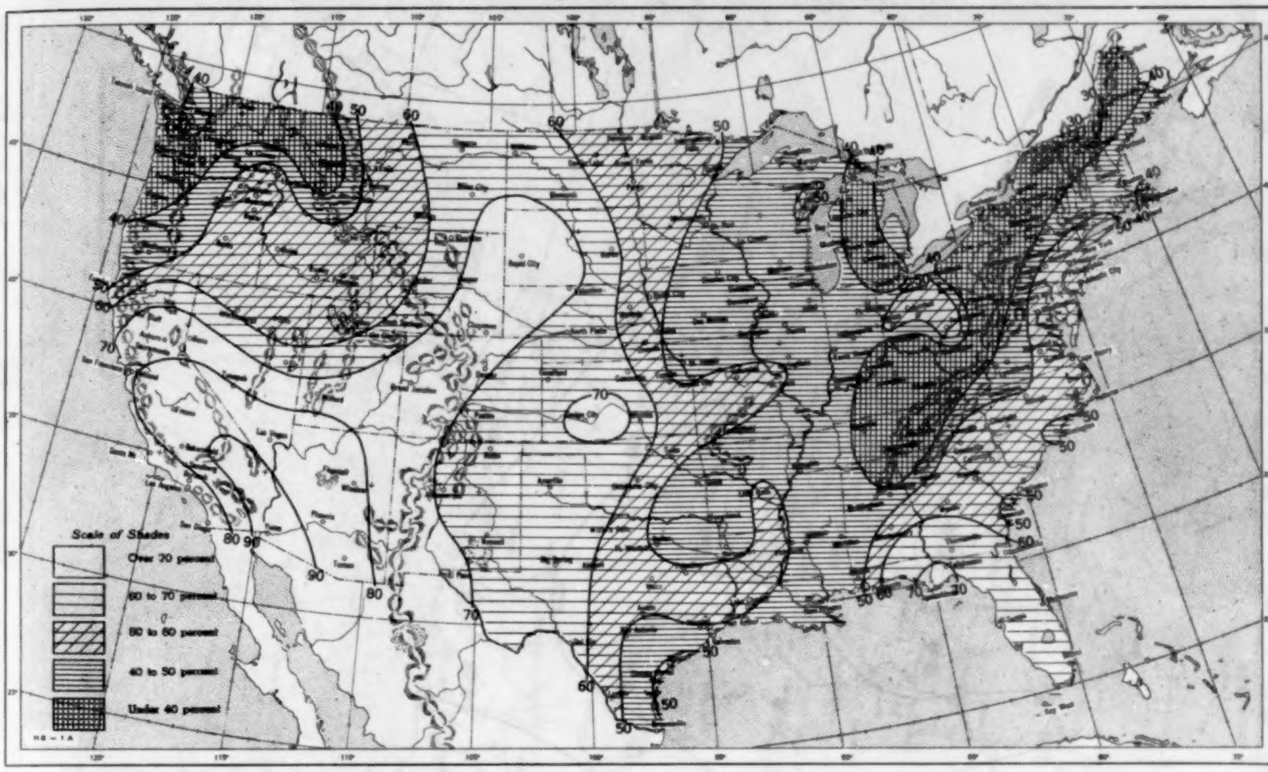



## B. Percentage of Normal Sky Cover between Sunrise and Sunset, March 1951.

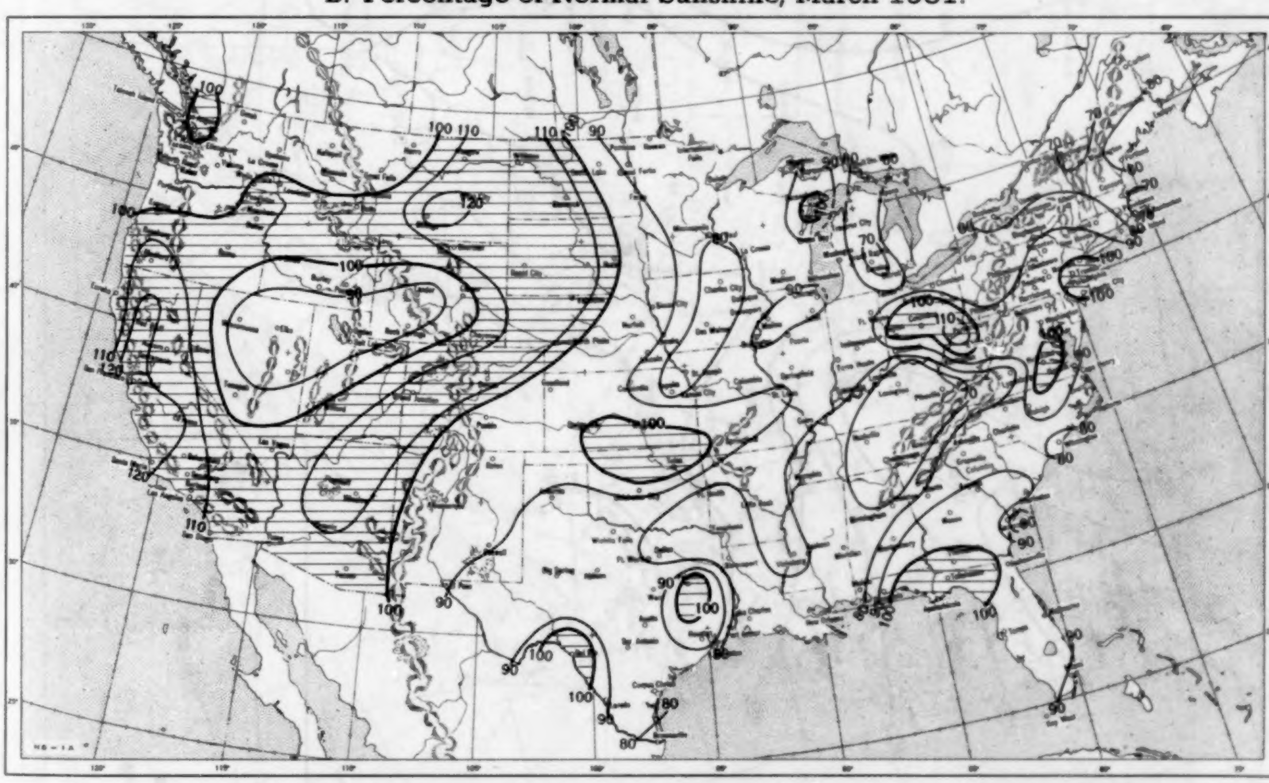


A. In addition to cloudiness, sky cover includes obscuration of the sky by fog, smoke, snow, etc. Chart based on visual observations made hourly at Weather Bureau stations and averaged over the month. B. Computations of normal amount of sky cover are made for stations having at least 10 years of record.

## Chart VII. A. Percentage of Possible Sunshine, March 1951.




## B. Percentage of Normal Sunshine, March 1951.



A. Computed from total number of hours of observed sunshine in relation to total number of possible hours of sunshine during month. B. Normals are computed for stations having at least 10 years of record.

Chart VIII. Average Daily Values of Solar Radiation, Direct + Diffuse, March 1951. Inset: Percentage of Normal Average Daily Solar Radiation, March 1951.

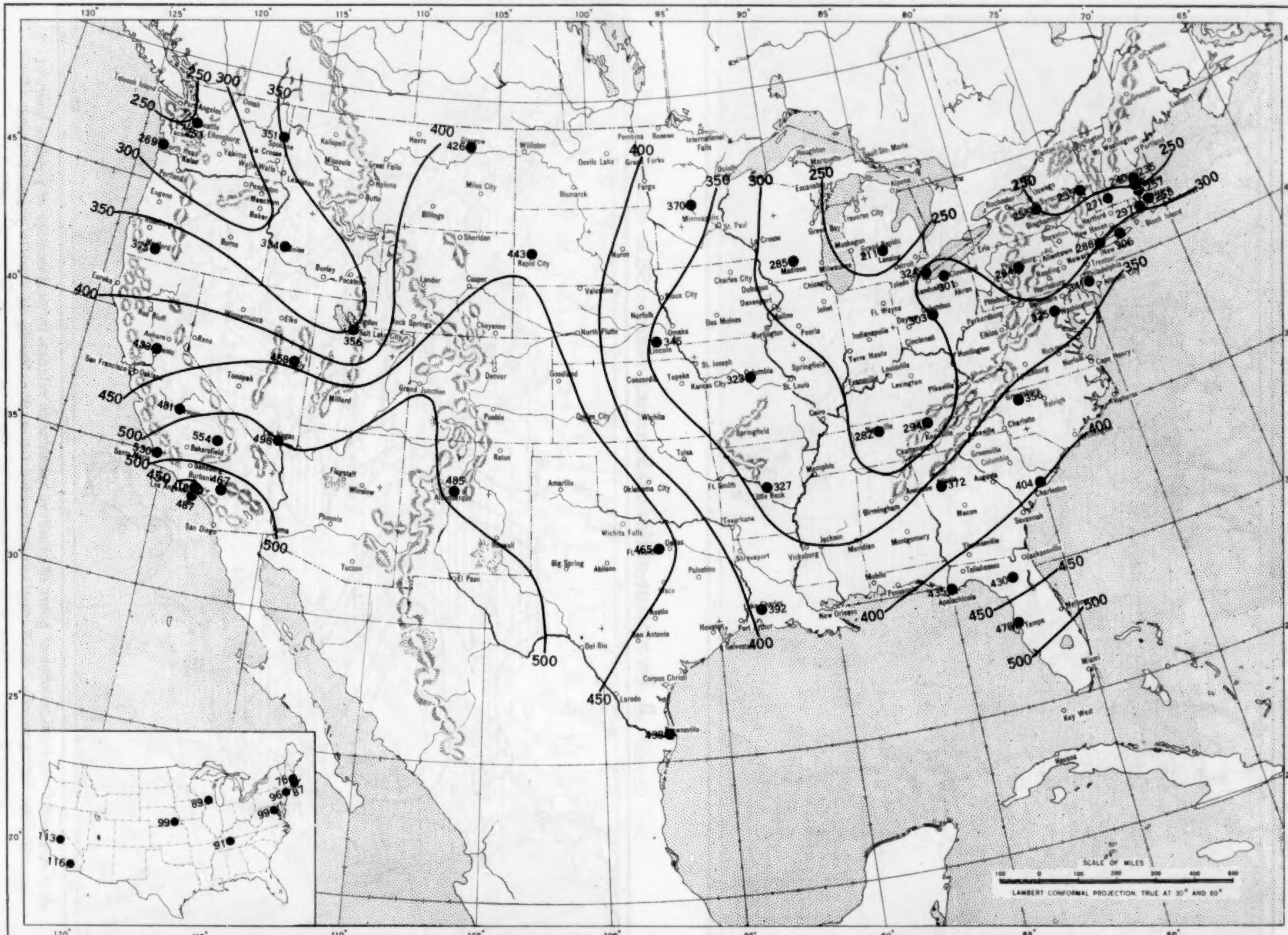
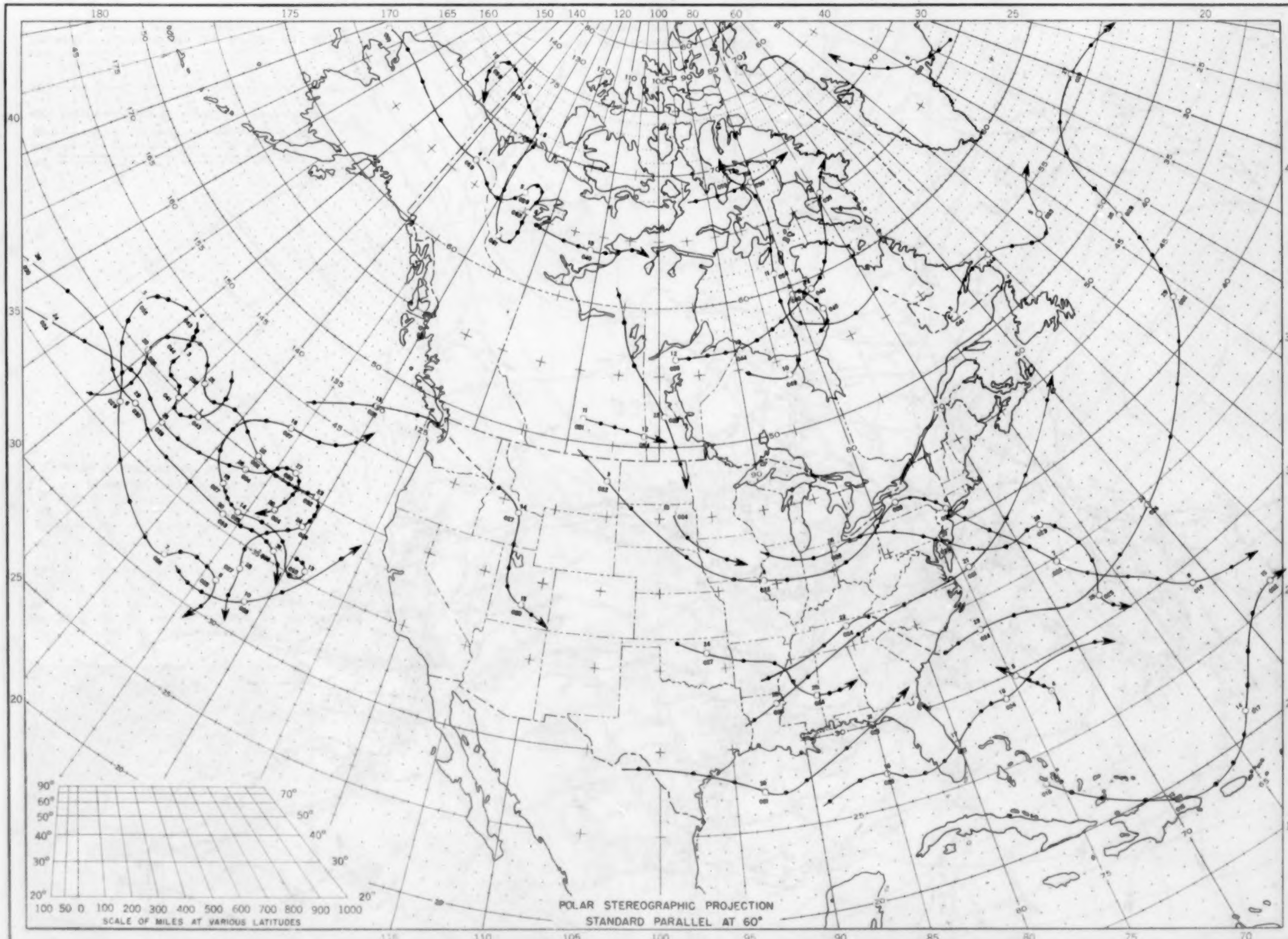


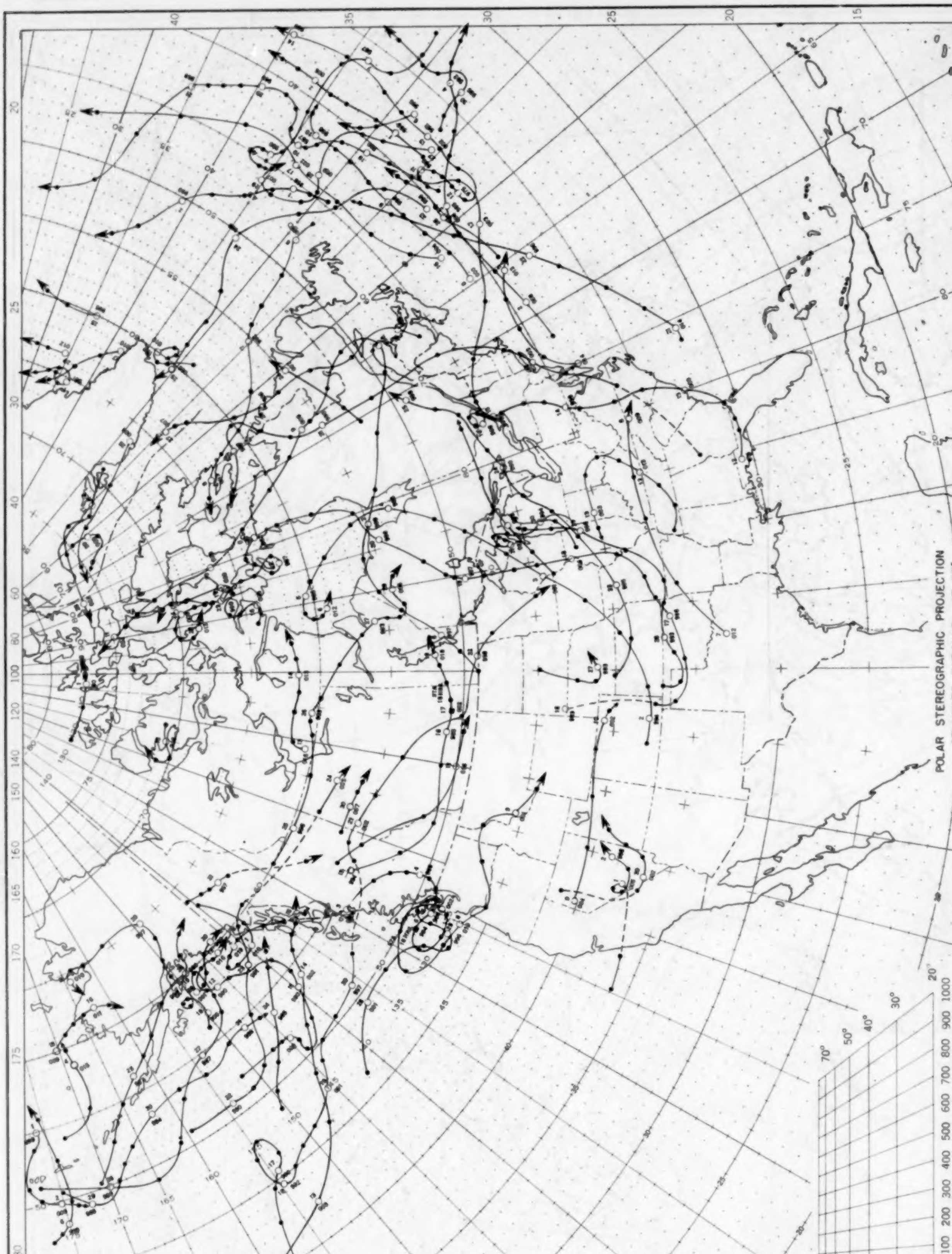
Chart shows mean daily solar radiation, direct + diffuse, received on a horizontal surface in langleys (1 langley = 1 gm. cal. cm. $^{-2}$). Basic data for isolines are shown on chart. Further estimates obtained from supplementary data for which limits of accuracy are wider than for those data shown. Normals are computed for stations having at least 9 years of record.

Chart IX. Tracks of Centers of Anticyclones at Sea Level, March 1951



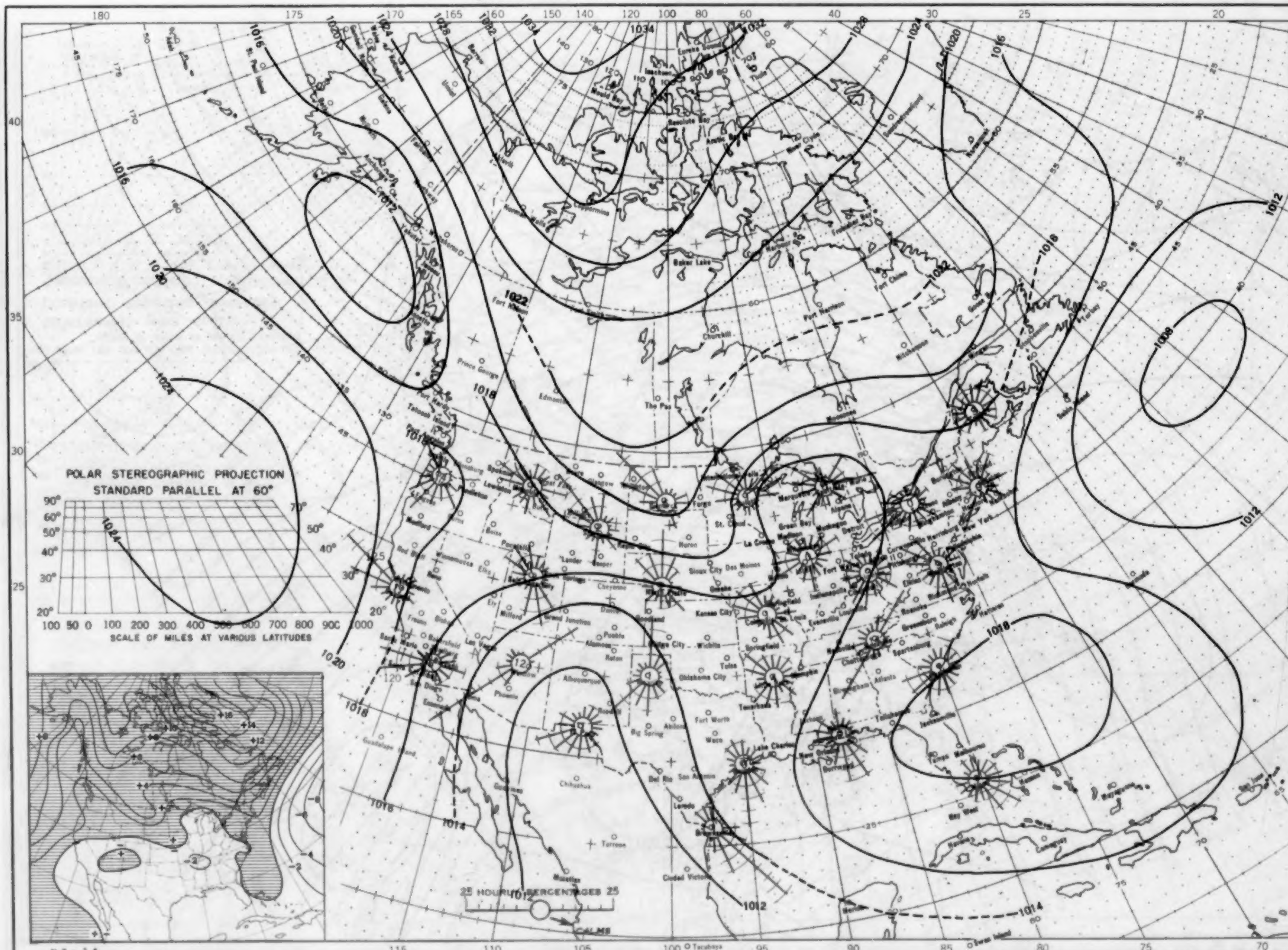

Circle indicates position of center at 7:30 a. m. E. S. T. Figure above circle indicates date, figure below, pressure to nearest millibar. Dots indicate intervening 6-hourly positions. Squares indicate position of stationary center for period shown. Dashed line in track indicates reformation at new position. Only those centers which could be identified for 24 hours or more are included.

Chart X. Tracks of Centers of Cyclones at Sea Level, March, 1951.



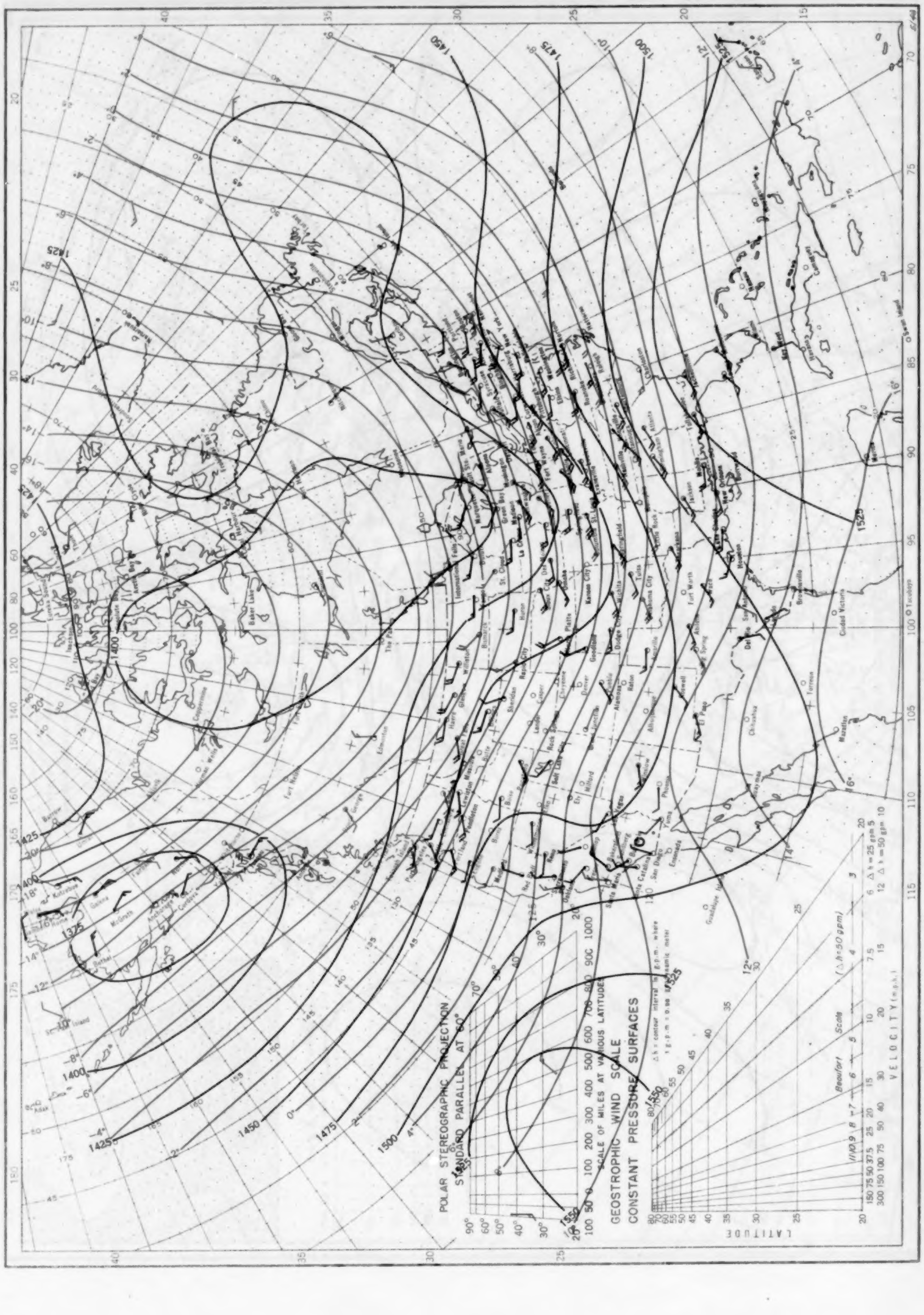

Circle indicates position of center at 7:30 a. m. E. S. T. See Chart IX for explanation of symbols.

Chart XI. Average Sea Level Pressure (mb.) and Surface Windroses, March 1951. Inset: Departure of Average Pressure (mb.) from Normal, March 1951.



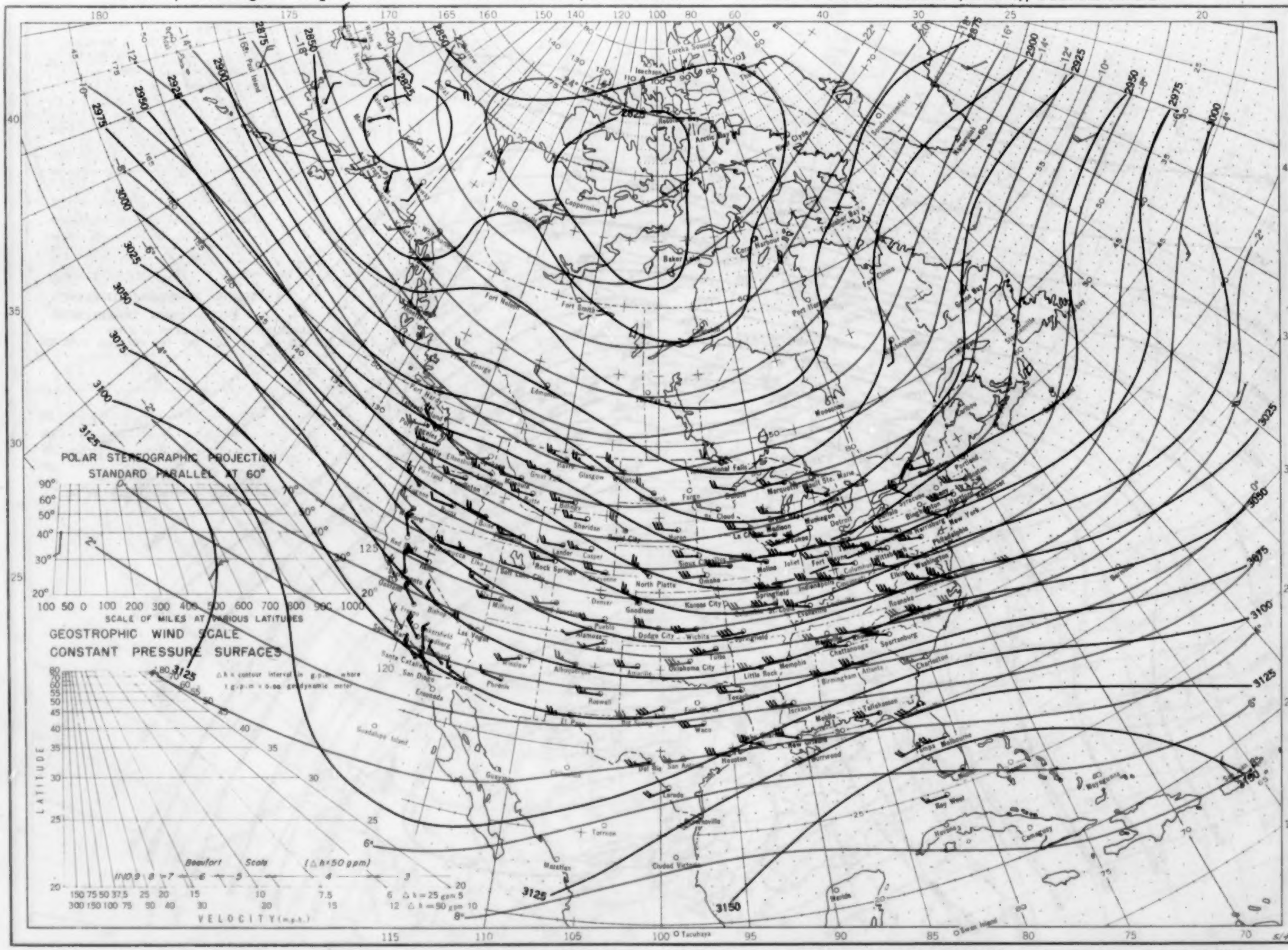

Average sea level pressures are obtained from the averages of the 7:30 a. m. and 7:30 p. m. E. S. T. readings. Windroses show percentage of time wind blew from 16 compass points or was calm during the month. Pressure normals are computed for stations having at least 10 years of record and for 10° intersections in a diamond grid from map readings for 20 years of the Historical Weather Maps, 1899–1939.

Chart XII. Average Dynamic Height in Geopotential Meters (1 g.p.m. = 0.98 dynamic meters) of the 850-mb. Pressure Surface, Average Temperature in °C. at 850 mb., and Resultant Winds at 1500 Meters (m.s.l.), March 1951.



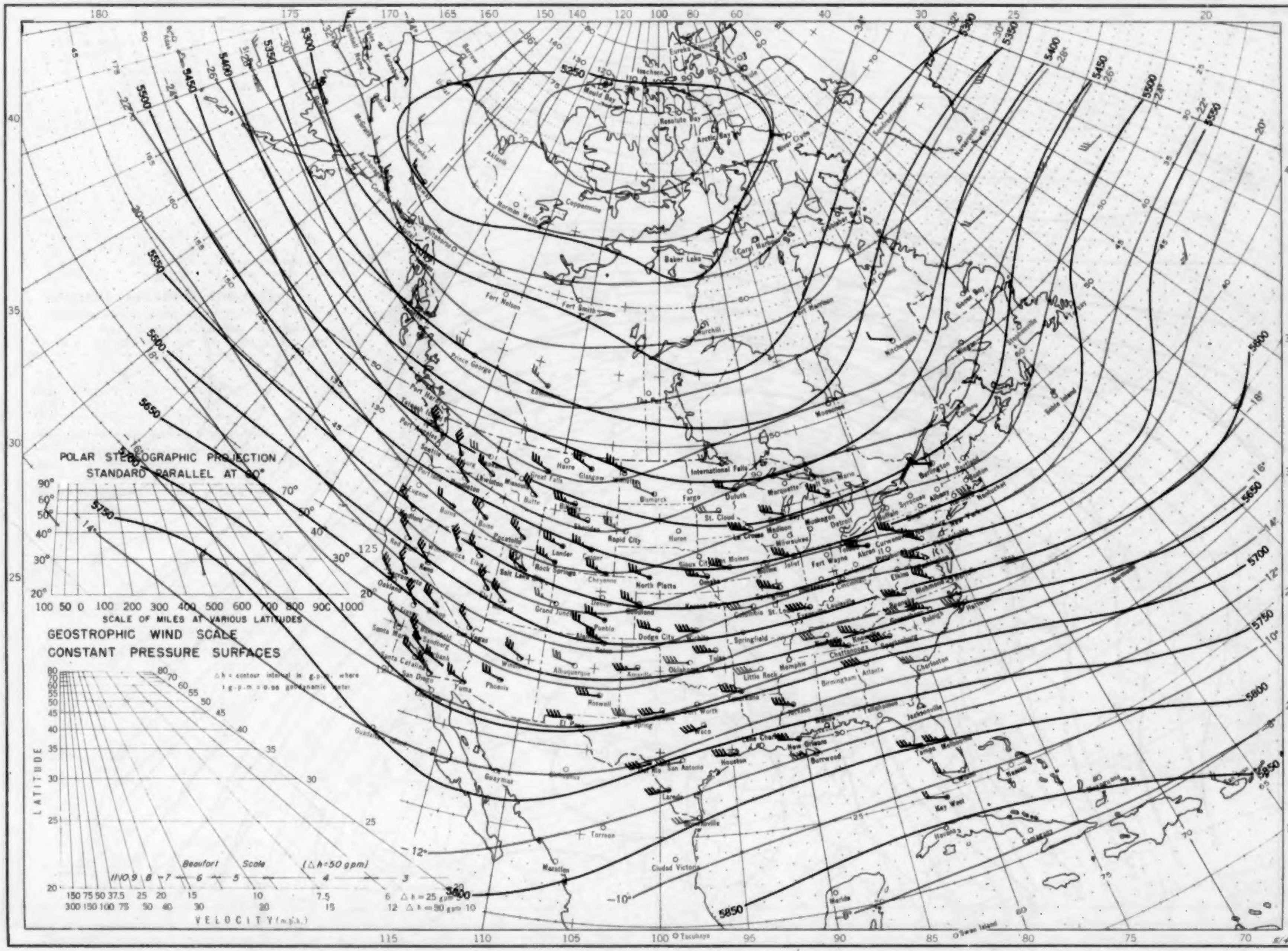

Contour lines and isotherms based on radiosonde observations at 0300 G. M. T. Winds shown in black are based on pilot balloon observations at 2100 G. M. T.; those shown in red are based on rawins taken at 0300 G. M. T.

Chart XIII. Average Dynamic Height in Geopotential Meters (1 g.p.m.. = 0.98 dynamic meters) of the 700-mb. Pressure Surface, Average Temperature in °C. at 700 mb., and Resultant Winds at 3000 Meters (m.s.l.), March 1951.



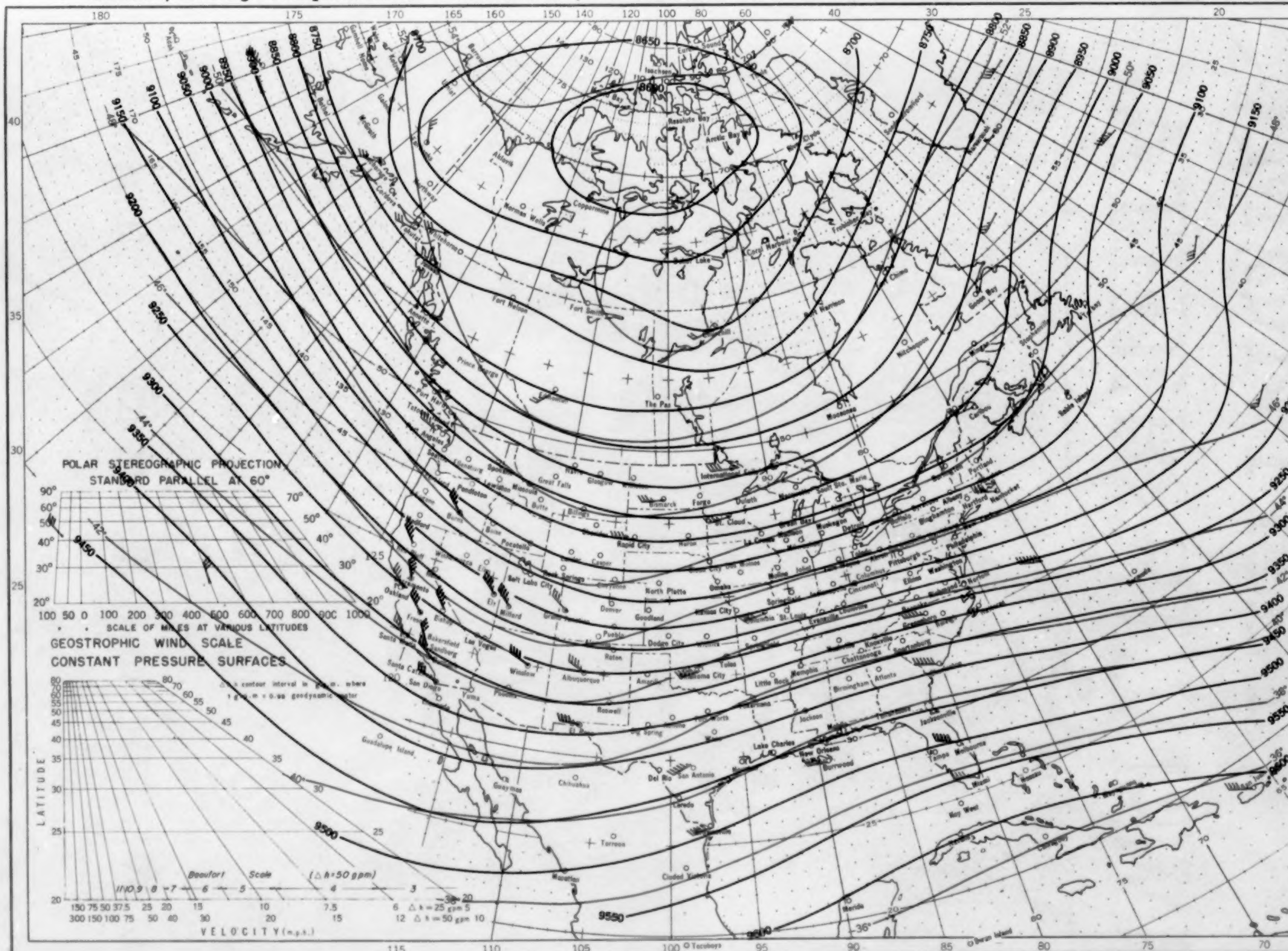

Contour lines and isotherms based on radiosonde observations at 0300 G. M. T. Winds shown in black are based on pilot balloon observations at 2100 G. M. T.; those shown in red are based on rawins taken at 0300 G. M. T.

Chart XIV. Average Dynamic Height in Geopotential Meters (1 g.p.m. = 0.98 dynamic meters) of the 500-mb. Pressure Surface, Average Temperature in °C at 500 mb., and Resultant Winds at 5000 Meters (m.s.l.), March 1951.




Contour lines and isotherms based on radiosonde observations at 0300 G. M. T. Winds shown in black are based on pilot balloon observations at 2100 G. M. T.; those shown in red are based on rawins at 0300 G. M. T.

Chart XV. Average Dynamic Height in Geopotential Meters (1 g.p.m. = 0.98 dynamic meters) of the 300-mb. Pressure Surface, Average Temperature in °C. at 300 mb., and Resultant Winds at 10,000 Meters (m.s.l.), March 1951.




Contour lines and isotherms based on radiosonde observations at 0300 G. M. T. Winds shown in black are based on pilot balloon observations at 2100 G. M. T.; those shown in red are based on rawins at 0300 G. M. T.